Developments in Paleoenvironmental Research 22

Valentí Rull
Christopher Stevenson *Editors*

The Prehistory of Rapa Nui (Easter Island)

Towards an Integrative Interdisciplinary Framework

Springer

Developments in Paleoenvironmental Research

Volume 22

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Editors

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ISSN 1571-5299 ISSN 2215-1672 (electronic)
Developments in Paleoenvironmental Research
ISBN 978-3-030-91126-3 ISBN 978-3-030-91127-0 (eBook)
https://doi.org/10.1007/978-3-030-91127-0

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Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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Chapter 1
Introduction

Valentí Rull and Christopher Stevenson

1 The Enigmas of Rapa Nui

The ancient and still enigmatic Polynesian society that lived in Rapa Nui (Easter Island) before European contact (1722 CE, common era) has fascinated scientific and popular audiences for generations. The remoteness of the island and its intermediate position between Polynesia, to the west, and South America, to the east (Fig. 1.1), has boosted the debate between the time of settlement and the origin of the first settlers. Although the aboriginal and the modern cultures are clearly of Polynesian origin, the possible influence of Amerindian (or Native American) cultures has been suggested throughout history. The better-known advocate of an Amerindian origin for the first colonizers was the Norwegian explorer Thor Heyerdahl, who organized the famous *Kon-Tiki* expedition that, in 1947, navigated from the Peruvian coast to the Tuamotu Islands (Fig. 1.1) using a wooden raft propelled only by wind and marine currents (Heyerdahl 1952). For Heyerdahl, this demonstrated that Native Americans could have arrived to Easter Island with their rudimentary navigation technology. Some years later, Heyerdahl led an expedition to Rapa Nui and supported his idea by survey and excavation of the abundant archaeological remains that, according to the explorer, were mostly of Amerindian origin (Heyerdahl and Ferdon 1961). Heyerdahl's beliefs were first accepted but strongly opposed after reanalysis of the available evidence (Flenley and Bahn 2003).

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_1

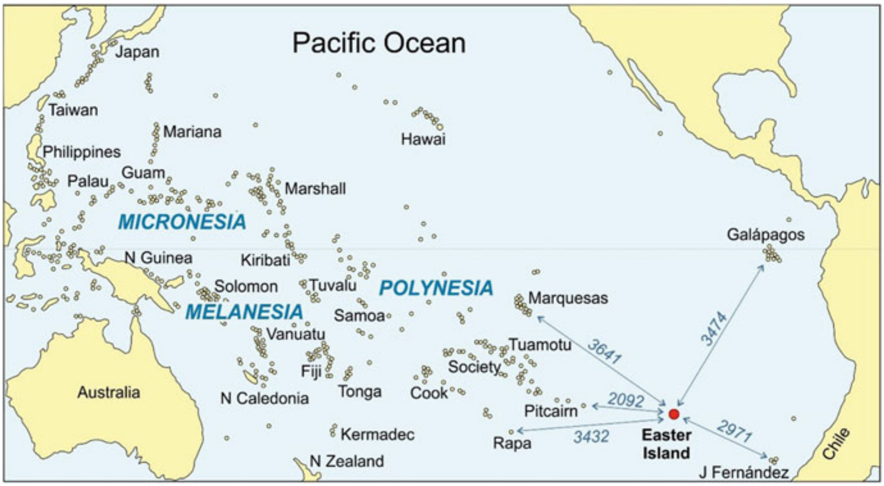

Fig. 1.1 The Pacific Ocean and its main archipelagos. Rapa Nui is represented by a red dot and the distances, in km, to the nearest Polynesian and American archipelagos are indicated. Modified from Rull (2020)

The spectacular development of molecular genetic analytical techniques during the last decades reopened the debate, which is still ongoing (Thorsby 2016). The time of discovery and first settlement of the island also remains a mystery, as different authors situate these events between 400 CE and 1300 CE (Kirch 2010; Wilmshurst et al. 2011; Flenley and Butler 2018; Hunt and Lipo 2018).

The most iconic manifestations of the ancient Rapanui culture are the nearly 1000 megalithic statues known as *moai* (Van Tilburg 1994) (Fig. 1.2). The main enigmas surrounding these monuments deal with their construction, transportation, and cultural meaning. The first European explorers wondered how the relatively small Rapanui population they encountered could have carved, transported, and erected these giant sculptures without resources such as wood (the island was deforested by the time of European contact), metals, and the associated technology (Fischer 2005). Today, it is known that the *moai* were carved on soft rock (tuff) using harder tools made of basalt, and that these statues represented deified ancestors like former clan chiefs, whose worship was intended for fertility and prosperity (Edwards and Edwards 2013). However, the technology used to transport these megalithic statues and emplace them on their altars (*ahu*) remains speculative. Several transportation techniques have been proposed and some of them have been tested in the field using *moai* reproductions, wood, ropes, and a significant number of people (Hunt and Lipo 2011). However, all these methods are imaginative procedures based on present-day ingenuity and the lack of irrefutable archaeological evidence, drawings, and written documents prevents demonstrating what was the actual means of *moai* transportation and emplacement. Beyond the *moai*, there are many other archaeological remains all over the island totaling about 20,000

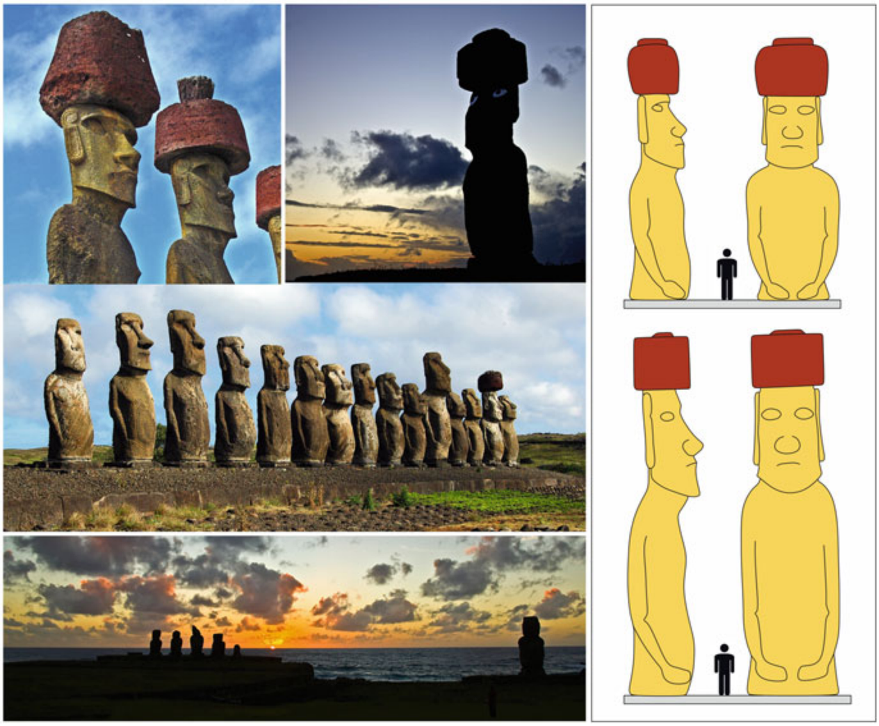

Fig. 1.2 Left: Some examples of *moai* on their respective *ahu* (Photos: V. Rull and N. Cañellas-Boltà). Right: Size comparisons of the biggest *moai* with an average human

stone features that are still preserved in their original location (Vargas et al. 2006). This is why the American archaeologist William Mulloy, who was part of the abovementioned Heyerdahl's expedition to the island, considered Rapa Nui as "the most spectacular potential outdoor museum to be found anywhere in Polynesia" (Mulloy 1974).

Easter Island is also famous for the internal cultural collapse of the pre-contact Rapanui society that erected the *moai*. It was Mulloy (1974) who launched the idea that at initial settlement the island was covered by a dense forest. After arrival the forest was totally cleared by the Rapanui settlers who used the wood and other plant parts for construction and *moai* transportation. According to this author, this was one more manifestation of the general overexploitation of the island, which ended with the depletion of many natural resources and the ensuing demise (in demographic and cultural terms) of the Rapanui society. Further palaeoecological studies developed by the British palynologist John Flenley and his coworkers demonstrated that, indeed, the island was covered by dense palm-dominated forests for more than 30,000 years (Fig. 1.3), before its total disappearance during the last millennium (Flenley and King 1984; Flenley et al. 1991). The approximate chronological coincidence of the forest removal with the Polynesian settlement of

Fig. 1.3 Comparison between a hypothetical reconstruction of former Rapa Nui's palm forests (above) and the present landscape (below) on the Poike Peninsula. Images courtesy of Andreas Mieth

Rapa Nui was used by these authors as evidence for Mulloy's self-induced cultural collapse hypothesis—also called ecocide by some authors (Diamond 2005)—and presented as an example of what could be the future of the whole Earth if current overexploitation practices continued (Bahn and Flenley 1992). This ecocide hypothesis dominated the scientific and non-scientific scenes for decades and is still accepted by many researchers and popular media. However, recent archaeological and palaeoecological evidence challenges the collapse idea and supports the scenario that the Rapanui culture did not collapse but remained healthy and prosperous until European contact, even in the absence of a forest (Mulrooney 2013; Stevenson et al. 2015). As a consequence, the real collapse of the Rapanui culture occurred after European contact, in the 1860s–1870s, and was caused by slave raiding and the introduction of alien epidemic diseases such as syphilis, smallpox, or tuberculosis (Fischer 2005; Boersema 2015). Some authors have called this collapse a genocide (Peiser 2005).

Whether the ancient Rapanui society suffered a demographic collapse, or was resilient to total island deforestation, this ecological shift initiated a profound change in the Rapanui culture that affected social, political, and religious aspects. The ancient religion, based on the *ancestor worship* and a strict hierarchical society with a dynastic successional system, was progressively replaced by the Birdman cult, where the maximum authority of the island (the *Ariki Mau*) was renewed every year from among the different clan chiefs (Routledge 1919; Métraux 1940; Englert 1948). The causes for this deep cultural change are still poorly understood although the defenders of the collapse hypothesis believe that the lack of wood and plant material prevented the continuity of the *moai* fabrication and megalithic architecture in general. At the same time, the onset of social conflicts, wars, and cannibalism, exacerbated by the lack of natural resources to maintain former population levels, could have determined a demographic collapse and a deep change in lifestyle (Bahn and Flenley 1992). Others suggest that, in a more resilient scenario, a territorial restructuring in response to soil nutrient depletion and a long period of dryness could have been involved (Robinson and Stevenson 2017). The chronology of this last episode of cultural change is also uncertain and ranges from the sixteenth century to after the European contact (Lee and Liller 1987; Pollard et al. 2010). The Birdman cult implied the development of a new symbology represented mainly by a widespread petroglyph industry, also called rock art, with more than 4000 petroglyphs (*rona*) still preserved (Lee 1992) (Fig. 1.4).

Another controversial topic has been the potential influence of climatic changes in the prehistory of Rapa Nui. This possibility had not been considered until the palynological surveys of Flenley and his team, who suggested the possibility of climatic shifts during the last millennia but not of sufficient intensity to cause the observed vegetation changes, especially the total forest removal. These authors argued that if Easter Island's forests had survived the pronounced and extended fluctuations in temperature and moisture balance that occurred between the Late

Fig. 1.4 Petroglyphs (*rona*) carved on basalt in the ceremonial site of Orongo, where the Birdman ceremony took place. Photo: V. Rull

Pleistocene and the Middle Holocene, including the Last Glacial Maximum, it would be unreasonable to assume that they could have been annihilated by the comparatively lower climatic variability of the Late Holocene (Bahn and Flenley 1992). Other authors suggested that global and quasi-global climatic changes such as the Medieval Warm Period (750–1250 CE) or the Little Ice Age (1350–1800 CE) could have had some influence on Easter Island's ecological and cultural trends (McCall 1993; Nunn 2007). However, these proposals were speculative as no evidence of climate change existed for the island. The first direct evidence of local climatic change on the island emerged roughly a decade ago, when Mann et al. (2008), using palaeoecological evidence from lake sediments (Fig. 1.5), suggested the occurrence of a drought, or a succession of droughts, of approximately 3000 years, ending by 1200–1300 CE. The last decade has witnessed a significant increase of palaeoecological work on Rapa Nui, and the establishment of a preliminary palaeoclimatic chronology for the last millennia, in relation to ecological and cultural developments (Rull 2021).

There are more mysteries and enigmas to solve in the prehistory of Rapa Nui but those summarized here may be considered the most notorious and widespread in both scientific and popular environments. Interested readers may increase their background by looking at the references cited, which constitute a representative selection of the existing literature.

Fig. 1.5 Lake Raraku, within the Rano Raraku crater. The sediments of this lake have been instrumental in deciphering palaeoecological trends on Rapa Nui. Photo: V. Rull

2 Aims and Scope

The enigmas of the ancient Rapanui culture have been addressed from a variety of scientific disciplines, notably archaeology, anthropology, ethnography, history, and palaeoecology. These disciplines have traditionally progressed in isolation with little interaction among them. Occasionally, some authors have tried to integrate evidence from several fields of knowledge but the main handicaps are the bias towards ones own approach and the difficulty of evaluating the evidence from alien disciplines. Sometimes, discussions among the different disciplines have developed into personal attacks with explicit political connotations (e.g., Flenley and Bahn 2007a, b; Hunt and Lipo 2007), which is contrary to the spirit of scientific research. The time has come to reverse these bad procedures and address the scientific research on Easter Island from a constructive multidisciplinary approach.

Understanding Rapa Nui prehistory, where environmental, ecological, and cultural processes and mechanisms constantly interact, requires a synergistic approach among the different disciplines. Active transdisciplinary collaboration among researchers from disparate fields is needed to pave the way towards more general hypotheses that may lead to more holistic views of the Rapa Nui prehistory. Palaeoecology, archaeology, anthropology, ethnography, history, and related disciplines should be viewed as complementary rather than excluding sciences whose practitioners compete for an imaginary right, unique, and definitive evidence from their own fields. Each of these disciplines is part of the same puzzle and we should learn how to assemble it together instead of claiming the absolute truth using only our particular, always incomplete, set of pieces (Rull 2020).

Ideally, collaboration should begin with the formation of multidisciplinary research teams and the careful selection of interdisciplinary research methods, as well as the definition of a synthetic framework able to account for the complexity of the whole socioecological system. This is not an easy task and requires previous initiatives addressed to gather and analyze the existing interdisciplinary knowledge and to test and/or develop suitable synthetic frameworks. The main aim of this book is to take the first steps in that direction.

To achieve this, we did an extensive literature review and invited all researchers and research teams who are, or have been, actively working and publishing on Rapa Nui. No one was excluded. Almost a hundred researchers representing as many disciplines as possible were included in the list. As usual, a portion of these scholars never answered and others politely declined the invitation. About the half of the requested researchers agreed to contribute and the initial book proposal consisted of ca. 40 chapters. However, almost half of these promised manuscripts were never submitted, with or without an explanation. Only a couple of the submitted manuscripts were withdrawn during the review process, whose only aim was to improve the manuscripts (none were rejected). Finally, the book is now composed of 22 chapters (plus the Introduction and the final Synthesis), by 55 contributors (see the List of Contributors), organized thematically, rather than by discipline, as explained in the next section. We are aware that it is not usual to give these numbers but we consider that it is important to emphasize that the book was open to any contributor from any research field.

Obviously, the book is neither a thorough compilation of the existing knowledge about Rapa Nui prehistory nor an exhaustive update. However, the book contains representative samples of the latest studies developed on the island and the state of the art of the different disciplines. At the end of the book, a first attempt to synthesize the most relevant multidisciplinary knowledge into a holistic framework is presented using the information provided in the preceding chapters and the most relevant literature. We hope that this book may be useful to help developing truly multidisciplinary research on Easter Island. This is our contribution to the venture and now we rely on the constructive scientific attitude and the good faith of researchers working on Rapa Nui.

3 Book Organization

The book is subdivided into six main parts. The first part is entitled *Transpacific voyaging and settlement* and is composed of five chapters. Anderson (Chap. 2) starts off the book by considering a question raised over 150 years ago; was there contact between South America and Easter Island? A century of debate and investigation has not been able to resolve the details of interaction but the evidence is accumulating for a more direct involvement of persons from Peru. There are complex similarities in architectural features between the two regions such as *tupa*, birdman motifs, and the *ahu* Tahiri (ahu no. 1) at Vinapu, the latter which contains so many design similarities that the direct involvement of an Inkan craftsman is seen as highly probable. Now with the application of improved radiocarbon methods there is also a time convergence between the two cultures. But how did an Inkan craftsman get to Rapa Nui? Maybe by a balsa log raft, which was a well-developed and sturdy seafaring technology developed in southern Ecuador for which there is evidence of usage on the open ocean in the second millennium CE. Equipped with such a craft, the likelihood of the movement of people and ideas into Polynesia from the east becomes increasingly real.

In Chap. 3, Thompson et al. address the problem of Rapa Nui settlement using domesticate/commensal plant and animal species that the colonizers transported as resources to survive in the newly colonized land; a modification that also made the island a comfortable place to live and similar to their ancestral homeland. The clearest evidence of products coming from the west (Polynesia) are bananas, chickens, Pacific rat, paper mulberry, sugarcane, taro, and yams. However, the presence of sweet potato and bottle gourd may have been the result of later trade, including contact with South America. The translocation histories of these nine domesticate/commensal plants and animals are used by Thompson et al. to clarify the migration routes used by the early Rapa Nui colonizers.

Muñoz-Rodriguez et al. (Chap. 4) provide the reader with a botanical background to one of the most important crops on Rapa Nui, the sweet potato (*Ipomoea batatas*). Along with taro and yam, the sweet potato was the staple food and backbone of the Rapa Nui economy. The authors bring a critical eye to how the evidence for sweet potato in the Pacific region is evaluated. They have waded through large numbers of documents to find those with original evidence and then evaluate them to identify ambiguities that may result in the mis-identifications with other members of the genus *Ipomoea*, the morning glory. Methodological issues in the identification of macro specimens, pollen grains, and starch and shortcomings with these methods as applied to Rapa Nui are identified and the general conclusion is that "the utility of most archaeological remains to enable differentiation between cultivated sweet potato, non-cultivated sweet potato and other species of *Ipomoea* is unsatisfactory". Despite these issues, human introduction of sweet potato that occurred around 1300 CE is supported, but caution must be exercized in making identifications.

Van Tilburg et al. (Chap. 5) present their discovery of the first directly dated and well-contextualized example of sweet potato on Rapa Nui from the excavation of *moai* 156/157 within the interior of the Rano Raraku statue quarry. Directly dated specimens of sweet potato are relatively few in the Pacific archaeological record and this example assists with the problem of origins. Equally important is the relevance of this and other dated specimens to the time range of agricultural activity within the quarry. Used in conjunction with 20 other radiocarbon dates on short-lived species the authors estimate the duration of agriculture within the crater interior. These data serve as a proxy for *moai* production at Rano Raraku.

Wallin and Martinsson-Wallin (Chap. 6) reconsider their 1987–1988 results from the excavations at *ahu* Nau Nau and focus on an area which they call *ahu* Nau Nau East located about 50 m to the north. After the initial excavations, the sector was interpreted as an associated ritual area attached to the main *ahu*, but redating of the space show it to be in line with the earlier initial settlement phase of Rapa Nui. Located beneath the deep beach sands was an artefact rich cultural layer with refuse pits containing food remains, postmolds, a stone alignment, fire pits, and a small vertically-set stone figurine. Taken together the area is interpreted as an early ritual space, possibly partitioned by a fence (the alignment) behind which feasting and sacrifice may have taken place. This early, and unique, ritual area is soon to be replaced by construction of megalithic architecture so characteristic of Rapa Nui.

The second part of the book is entitled *The ancient Rapanui culture* and is composed of four chapters. Stevenson et al. (Chap. 7) offer a new interpretation for the archaeological feature known as the refuge cave or *ana kionga*. Initially identified by explorer La Perouse in 1786, this type of cave with a narrow tunnel entrance was a major piece of supportive evidence for the collapse theory as it was seen as an archaeological correlate for internal warfare. Detailed excavations reveal that not only the entrance, but the interior, is architecturally modified and contains prepared clay floors and platforms. The extent of modification suggests to the authors that the cave is not a refuge from violence, but rather, a prepared ritual space possibly connected with the Birdman cult. Accelerator mass spectrometry (AMS) radiocarbon and obsidian hydration dates put peak usage in the early 1800s CE but the exact beginning of cave modification and use is still unclear.

Martinsson-Wallin (Chap. 8) takes us to one of the most impressive ceremonial places on Rapa Nui, that of the *ahu* Vinapu complex. It was one of the first locations investigated on Rapa Nui by archaeologist William T. Mulloy. The architectural interpretation of Mulloy is reviewed in detail for two *ahu* and the two adjacent elite house complexes. This sets the context for the chapter which is to evaluate the early twelfth century radiocarbon date (M-710 BP 1100 ± 200) from underneath the earthwork embankment that surrounds the plaza of *ahu* No. 2. New AMS radiocarbon dates on nutshell from two contexts returned dates of 1304–1437 CE and 1303–1442 CE (2σ) and demonstrate a later date for ceremonial activities in this area than previously thought.

Cauwe and De Drapper (Chap. 9) address a long-held interpretation about the isolated *moai* that are found along the network of roads leading away from the statue quarry of Rano Raraku. Conventionally, these fallen, and sometimes broken, statues are interpreted to be accidents of transport and abandonment but two forms of evidence suggest otherwise. Morphologically the *moai* "in transport" are different in proportions than those present at *ahu* which raises the question of whether installation on an *ahu* was indeed the end goal. They also expand upon an observation made by Katherine Routledge in the early twentieth century that identified *moai* surface erosion patterns (runnels) which could only form if the statue was positioned vertically for an extended period. Taken together, this evidence suggests that the statues marked the road, possibly to help ensure safe travel of other *moai* to their platforms.

Cauwe (Chap. 10) tackles another theme of the Rapa Nui collapse scenario, that of the violent destruction of the *ahu* and toppling of the *moai*. Fallen statues and rock-covered *ahu* give the modern viewer a sense of disarticulation that is hypothesized to come from a society gripped by self-destruction. But nothing could be further from the truth. The author lays out a convincing case for *ahu* construction and ritual closure identified from his excavations. Closure is marked by the removal of sea cobbles from the structure and the applications of granular red scoria, and after a period, the *ahu* is rebuilt anew. Thus, each *ahu* has its own unique multi-phased life history. This activity of ritual closure extends to the final phase of prehistory where the *moai* are lowered and the entire structure covered with basalt field stone; never to be rebuilt again.

The third part of the book is entitled *Climatic and environmental change* and is composed of three chapters. Bradley et al. (Chap. 11) inaugurate this part by providing insights on the present Rapa Nui climate using instrumental data from a meteorological station situated at the airport (Mataveri). Emphasis is on rainfall amount and regime. Climatically, the island is under the influence of the Sub-Tropical High Pressure Zone (STHPZ) and the South Pacific Convergence Zone (SPCZ), with no significant long-term correlation between rainfall and the phase of the El Niño Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO). Daily rainfall amounts rarely exceed 100 mm and occur on about half of the days. Moisture sources are similar in both wet and dry years, and wet years result simply from the occurrence of more rainy days due to local synoptic conditions. During the last decade, rainfall has been well below the long-term average, which has significantly reduced the Rano Raraku lake to a small area of surface water. This is preliminary attributed to and expansion of the Warm Pool in the western Pacific, which has reduced rainfall east of the SPCZ.

Rull (Chap. 12) reviews the history of palaeoecological research on Rapa Nui and places the main findings in chronological context with the goal of realizing a more inclusive scientific framework for Easter Island prehistory. The discussion highlights climatic and ecological changes over the last millennium and the influences these factors may have had on sociocultural trends and events. Three main phases of palaeoecological research are recognized and include: the pioneer phase (1977–1992), the intermediate phase (1993–2004), and the revival phase (2005–present). The contribution of palaeoecology to developing a better understanding of Easter Island's prehistory is discussed with a focus on four main points: (1) the discovery and settlement of the island, (2) the occurrence of climatic changes and their natural and anthropogenic drivers, (3) spatiotemporal deforestation patterns, and (4) the potential relationship between climatic, ecological, and cultural shifts. Future research avenues are suggested that would make Rapa Nui research a more holistic scientific endeavour.

Sáez et al. (Chap. 13) describe the main geological features of Rapa Nui and their influence on human occupation and habitation. The petrological characteristics and age of the volcanic rocks forming the island have greatly conditioned not just the geomorphological and edaphic processes but also the raw materials used by humans for construction. The lithology has been fundamental in shaping the island's hydrology and water quality, which has had a great influence on human life and crop development. The sedimentary record of lakes and wetlands has uncovered climate changes that have significantly influenced deforestation. These authors also suggest that the occurrence of high-energy events such as tsunamis and long-distance volcanic eruptions may have influenced the island during the last millennium. They conclude that geological processes greatly influenced human settlement on Rapa Nui.

The fourth part of the book is entitled *Deforestation and extinctions* and is composed of five chapters. In Chap. 14, Zizka and Zizka compare the present flora and vegetation of Rapa Nui with the conditions before human arrival. They observed that the extant flora is dominated by alien species, most of which were introduced after European contact. The past flora, dominated by the *Paschalococos disperta* and the toromiro (*Sophora toromiro*) went extinct after human arrival. Under these conditions, reconstruction of the native flora and understanding its geographical origin is challenging. An updated list of potentially native species of flowering plants is provided, based on inventories, palynological records, and archaeological surveys from the literature. This list is then combined with information on potential native species from other plant groups (fern & allies, mosses, and liverworts), and the present-day geographical distribution of all these plants is used to infer geographic affinities for Rapa Nui's native flora.

Ingersoll et al. (Chap. 15) examine the potential implications of palm morphological and anatomical features (as compared to dicotyledon trees) in archaeological interpretation, especially for dendrochronology and radiocarbon dating. In the case of Rapa Nui, these authors evaluate the potential role of the extinct palm *Paschalococos disperta* (related to the arecoid palms *Jubaea*, *Cocos,* and *Roystonea*) in relation to cultural uses such as canoe building, *moai* transport, and raw material for construction.

In Chap. 16, Steiglechner and Merico use mathematical models to evaluate important aspects of the pre-contact Rapanui culture such as the maximum size of human populations and the spatiotemporal deforestation dynamics. The main handicap of previous models was the lack of consideration for human decision-making and environmental heterogeneities. These authors introduce age-based models that consider these elements, as well as their interactions. Results indicate that patterns of deforestation, settlement, and land use vary from region to region, not only according to environmental heterogeneities but also human decisions, as for example moving from one area to another. This suggests that Rapa Nui prehistory is complex and cannot be captured by simple island-wide narratives.

Brander (Chap. 17) presents an economic and ecological model (EEM) of the interaction between the indigenous palm forest and the Rapa Nui population prior to first European contact. The model, which is a revision and reconceptualization of the problem published in 1998 by the same author, seeks to explain the pattern of deforestation over time and how it correlates with demographic trends. To mathematically model the functional relationships between variables of the forest, the people, and the economy, the data on each component is reviewed and the parameters and assumptions behind the simulation are developed. A simulation base case is run and it shows the expected boom-and-bust relationships between declining forest resources, population size, and per capita utility. Then, key parameters are varied to produce four alternative outcomes which highlight the relative importance of each variable. The best available evidence to date produces a weaker version of the catastrophe model where the population stabilizes at a relatively low level at the point of European contact.

In Chap. 18, Wozniak conducts detailed archaeological and geomorphological studies in Te Niu, on the northwest coast of Rapa Nui, to document a significant landscape change consisting of the long-term conversion of a palm-dominated forest to a food-production area. Archaeological excavations and dating (radiocarbon and obsidian hydration dates) provided evidence of the transformation of the original forests to gardens after 1300 CE and to grazing lands in the late nineteenth century. Geomorphological and hydrological evidence indicates that these transformations resulted in repeated erosion/sedimentation episodes. The shift from forest to croplands occurred after Polynesian settlement and the shift to grasslands took place after European contact, when the island was transformed into a ranch for imported sheep.

The fifth part of the book is entitled *Collapse or resilience?* and is composed of four chapters. Mieth et al. (Chap. 19) present a summary and interpretation of their extensive excavations at *Ava Ranga Uka a Toroke Hau*, located on the upper slopes of Maunga Terevaka. This complex of features consists of an *ahu* platform and *moa*i, monumental terraces, elaborate water basins, canals, and superimposed stone pavements that straddle the upper reaches of the seasonal stream known as Quebrada Vaipú. Water was the focal point for this site but it was not directed into agricultural fields. Domestic settlements are rare and everyday access to the larger Rapa Nui population is inferred to have been restricted. The emphasis seems to have been on the preparation and use of a ritual space for fertility rituals where women may have been bathed during the birthing process. The complex stratigraphy of the complex suggests periods of ritual closing and refurbishment characteristic of other large-scale architecture. Radiocarbon dating places the use of the complex at c. 1270–1670 CE which was terminated when a catastrophic flood event tore through the sequence of superimposed pavements and covered the large-scale pigment production fields located just below the ritual complex.

In Chap. 20, Puleston and Ladefoged present two population models based on the idea of carrying capacity to estimate the maximum number of people who might be fed in a given place with a given agricultural and technological toolkit. Then, they apply these models to Rapa Nui in the period before European contact. The first model considers surplus production beyond subsistence requirements and work load. The second model is more dynamic and adjusts demographic rates in response to food availability, eventually approaching an equilibrium. The application of these models to prehistoric Rapa Nui is constrained by the uncertainty about the productivity of the island's agricultural system, which yields a wide range of possible population estimates. The predicted population sizes that are consistent with archaeological evidence result from model runs using low production rates.

Lima et al. (Chap. 21) develop a model based on the population dynamic theory (PDT) that integrates climatic, demographic, and ecological factors. In Rapa Nui, the model predicts sustained population growth between 1100 CE and 1400 CE, followed by further demographic declines. These results are consistent with variations in the El Niño Southern Oscillation (ENSO) activity, especially droughts, which modulates island's carrying capacity. Rapa Nui is viewed as a small and isolated island inhabited by an agrarian society facing resource scarcity, overpopulation, and climatic change. The suitability of PDT models to test predictions and explanations in such a situation is highlighted.

Lipo et al. (Chap. 22) look at the evidence that supports claims for large pre-European population size on Rapa Nui. When early navigators disembarked on Rapa Nui the number of persons was repeatedly estimated in the low thousands and visitors saw this as incompatible with the visible architecture. It was inferred that some catastrophic event had happened in the past to reduce population size. This reasoning has continued within modern archaeological research and the speculative estimates of pre-contact populations range between 7000 and 25,000 persons. The authors review the methods used to arrive at these population estimates such as house counts, resource abundance, and relative population size, and find the evidence lacking. They urge researchers to develop stronger measures for estimating population size in future research.

The sixth part of the book is entitled *European contact* and is composed of a single chapter. Boersema (Chap. 23) discusses two lesser-known accounts of a visit to Easter Island by the Dutch expedition led by Roggeveen in 1722. The writings appeared in 1727 and 1728 but have not been translated from the Dutch until now. Upon inspection, the accounts describe some of the same events as in the narrative of Roggeveen but differ significantly in the description of Rapanui women and men which are reported to be 10 and 12 ft in height. The question then becomes why did these exaggerations occur, why do people believe them, and is there a rational behind them? Psychologists believe there is an explanation and experimental studies show that a cultural bias heavily influences how factual information is interpreted by the observer. For example, in the eighteenth century, Europe giants are a part of Christian theology and this has an influential role in the eighteenth century observations where the citing of giants was not infrequent. This concept of word view and its influence on scientific thought is then discussed in relation to contemporary thinking about Rapa Nui prehistory.

The book is closed by a synthesis (Part 7; Chap. 24), written by the editors, aimed at progressing towards a holistic view of the island's prehistory that considers as many disciplines as possible. This synthetic chapter adopts a human ecodynamics approach where the functional unit is the socioecosystem, which is composed of three subsystems (environment, landscape, and humans) and their corresponding feedbacks and synergies (EHLFS system). Human behaviour in relation to the EHLFS dynamics has a special component characterized by creativity and decision-making, which is not present in other subsystems, and is analyzed here in terms of niche construction. Using these approaches, the prehistory of Rapa Nui and the first stages of European contact (ca. 800 CE to ca. 1800 CE) are subdivided into six states of the sociecosystem (EHLFS1 to EHLF6), which are described and characterized in terms of environmental–ecological–human complexity.

Acknowledgments The editors would like to thank the Springer Nature staff, especially the subject editor, Lars Körner, and the project coordinator, Parthiban Gujilan Kannan, for their enthusiasm and constant support. Of course, the book would not have been possible without the time and effort dedicated by all contributors who, despite the psychological and social stress caused by the COVID-19 epidemic, maintained their commitment until the end. Thank you very much to all of them. We also feel indebted to all reviewers for their accurate, thoughtful, and thorough reviews, which have been fundamental to guarantee the scientific quality of the book. These reviewers are (in alphabetic order and excluding editors): Atholl Anderson, Raymond Bradley, James Brander, Jean-François Butaud, Ethan Cochrane, Richard Dunn, Daniel Ingersoll, Holger Kreft, Thegn Ladefoged, Carl Lipo, Daniel Mann, Helene Martinsson-Wallin, Agostino Merico, Andreas Mieth, Cedric Puleston, David Sear, Dale Simpson, Fred Stauffer, Jillian Swift, Kevin Trenberth, Paul Wallin, Peter Waylen, and Georg Zizka.

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Part I
Transpacific Voyaging and Settlement

Chapter 2
Ex Oriente Lux: Amerindian Seafaring and Easter Island Contact Revisited

Atholl Anderson

1 Introduction

In archaeology, *ex oriente lux* (light from the east) refers to a model of cultural diffusion from western Asia to western Europe (Montelius 1885) that was adopted by Gordon Childe (1939), and epitomized as "the irradiation of European barbarism by Oriental civilization" (Childe 1958: 70). More recently, and stripped of its social-evolutionary labels, *ex oriente lux* has contextualized research on the dispersal of early ceramic technology in East Asia (Jordan and Zvelebil 2009), and I use it similarly here to approach the issue of putative South American residence in Easter Island (Rapa Nui).

The wider context of this enquiry is so well known as to require only a brief introduction. The pre-European existence in Easter Island of the South American sweet potato (*Ipomoea batatas*) and its name (Quechua *cumar* becoming Polynesian *kumara*) indicate that irrespective of whether kumara drifted or was carried to East Polynesia, there must have been contact between Amerindians and Polynesians, if only to transfer the name (Anderson and Petchey 2020; Muñoz-Rodríguez et al. 2018; Wallin 2014, 2020). One hypothetical explanation is that kumara and items or knowledge of material culture were carried into East Polynesia by Amerindian rafts (Emory 1933; Heyerdahl 1952). In direct contradiction, another hypothesis argues that sweet potato from South America was obtained exclusively by Polynesian return voyaging (Dixon 1934; Green 2001). From purported evidence of Polynesian chickens in south central Chile (Thompson et al. 2014; Herrera et al. 2020; *contra* Jones et al. 2011; Storey and Matisoo-Smith 2014), an older idea has been revived

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_2

of sailing from Polynesia to South America in temperate westerlies, coasting north to Ecuador-Peru, and returning to Polynesia in tropical easterlies. Separate one-way passages to Chile by Polynesians and from Ecuador by Amerindians would account more simply for the same data (Anderson et al. 2007).

In considering alternative propositions, it is important to acknowledge consensus about the origin of the first people on Easter Island. That they were Polynesian is indicated by bones and mtDNA of the Polynesian rat (*Rattus exulans*) in the oldest confirmed habitation site, at Anakena (Skjølsvold 1994: 114, Martinsson-Wallin and Crockford 2002: 259; Barnes et al. 2006). The point is significant here because it implies that any later non-Polynesian influence might have had little opportunity to reproduce its cultural inventory before being overtaken by hybridization or extinction in a dominantly Polynesian cultural milieu. New forms of material culture might have been competitively re-shaped quite briskly, leaving only partial traces of their original type or function. In that case, and in the absence of definite Amerindian evidence, e.g. of ceramics, obsidian, jade, or metals, Heyerdahl's (1952) largely homomorphic arguments for the existence of Amerindian material culture on Easter Island were fated to be studiously ignored (e.g. Sahlins 1955) or seen as ambiguous, partial, or unconvincing (e.g. Skinner 1955; Holmes 1958; Suggs 1960: 212–224), and they have continued to be debated up to the present.

A critical problem was the absence of persuasive evidence that pre-Columbian Amerindian people had ever lived on Easter Island. This is now changing as the result of recent human genetic research on Easter Island and across East Polynesia. Among various studies, some found no evidence of prehistoric Amerindian ancestry (e.g. Feren-Schmitz et al. 2017, by DNA analysis on several bone samples from *Ahu* Nau Nau), and others that there is evidence of pre-European Amerindian contact (e.g. Thorsby 2012, on HLA alleles but not in DNA analysis). Now, the latest analysis of genome-wide variation in human DNA from tropical East Polynesia indicates strong support for transfer of Amerindian DNA from Central America (notably Colombia and Ecuador) into the eastern archipelagos of Polynesia, especially the Marquesas, northern Tuamotus, Gambier Islands, and Easter Island (Ioannidis et al. 2020). The Amerindian-Polynesian admixture is estimated as occurring about AD 1150–1230 for all localities except Easter Island where it is set at about AD 1380. Moreno-Mayar et al. (2014) dated the prehistoric Amerindian-Polynesian genetic admixture on Easter Island to AD 1280–1495, and Thorsby (2016) to around AD 1340. Younger admixture could reflect relatively high Amerindian genetic input after about AD 1800 (Ioannidis et al. 2020), or several episodes of prehistoric Amerindian seafarers reaching the eastern margins of Polynesia (Wallin 2020).

The increasing probability that Amerindian people did reach Easter Island before the sixteenth century provides an impetus to reconsider the crucial and long-standing questions: how persuasive is the archaeological evidence of an American presence, and how might Amerindians have arrived there?

2 Amerindian Material Culture in Easter Island?

The earliest scholarly discussion about a possible Amerindian origin of monumental architecture on Easter Island seems to have been in January 1870 at a meeting of the Royal Geographical Society in London, following a paper by J. L. Palmer, Surgeon on the Royal Navy *Topaze*, about his visit to the island in 1868. C.R. Markham, an Inka specialist in the audience, said that "it was impossible not to be struck with the resemblance between [Inka] remains and those on Easter Island" (Palmer 1870: 117). However, in a manner presaging the larger debate to come, others in the audience including Sir George Grey, former Governor of New Zealand and schooled in Maori tradition, appealed so strongly to the Polynesian cultural and linguistic heritage of Easter Island that the Chairman conceded, "he was to a great extent convinced by the reasoning that had been opposed to the Peruvian theory" (Palmer 1870: 119). Later propositions of Easter Island influence carried by Polynesians to Peru (Imbelloni 1940), of Polynesian voyagers bringing Peruvian architecture to Easter Island (Handy 1927), and of Peruvian voyaging to Easter Island (Emory 1933) kept the issue alive. It was dismissed by Métraux (1940) in favour of independent local development of the architectural similarities, but only just ahead of influential support for the Amerindian diffusion model by Heyerdahl (1941).

The presence of Heyerdahl (1952) and Heyerdahl and Ferdon (1961) looms over any discussion of potential Amerindian influence in Easter Island prehistory to the extent that it is difficult to avoid covering much of the ground already worked over, indeed fought over, by him and his many critics. The latter were provoked, above all, by his hyper-diffusionist conceit of ancient Europeans carrying high civilization into the eastern Pacific (Holton 2004). More important, and seldom readily conceded, is that Heyerdahl's archaeological expeditions in the Pacific and South America produced abundant scholarly material pertinent to the question of prehistoric Amerindian-Polynesian contact. Consequently, and irrespective of arguments about how similarities should be explained, it is worth re-considering several types of material culture on Easter Island which bear particularly intricate resemblance to cognate items from the northwest Andean region of pre-Columbian South America and have no obvious antecedents in East Polynesia. These, noted in previous publication (Anderson et al. 2007; Martinsson-Wallin 1994; Martinsson-Wallin et al. 2013), are *Ahu* Vinapu 1, *tupa*, and birdmen.

2.1 *Ahu Vinapu 1 (Ahu Tahiri)*

Several *ahu* (ritual platforms) in Easter Island exhibit unusually accomplished, close-fitting masonry which has been attributed variously to local development of Polynesian technology (e.g. Métraux 1940: 289–291), or Amerindian influence (Emory 1933). On the Cook expedition in 1774, William Wales described rowing ashore in Hangaroa and seeing "a sort of breast work of very neat hewn stone which we conceived had been the work of some Europeans". Once ashore, and finding that it was a native edifice, he observed that "the workmanship was not inferior to the best plain piece of Masonry that I have seen in England" (Beaglehole 1961: 820–821; this was *Ahu* Hangaroa, later largely destroyed). Wales and others walked across the low ground from Hangaroa to the east coast at Vinapu where Johann Forster wrote that "in some places these elevations [i.e. *ahu*] are made of regularly hewn square stones, sitting as regularly & as finely as can be done by a Nation even with good tools. In what manner they contrived these structures is incomprehensible to me . . . " (Hoare 1982: III: 468–469). Forster recorded the *ahu* as Hanga-to-bow, referring to Te Pau bay at Vinapu, and it is almost certainly the one known now as *Ahu* Tahiri or *Ahu* Vinapu 1.

This has a seaward façade (Fig. 2.1) that, although damaged in 1886, is still strikingly evocative of pre-Columbian megalithic masonry in Bolivia and Peru particularly in the period of the Inkan state (AD 1400–1532). The façade exhibits many of the characteristics of high-status Inkan walls. It has slight curvature in plan shape with rounded corners, features noted especially in outlying regions of the Inkan empire (Hyslop 1990: 7–8). The blocks are of vesicular basalt, finely cut, precisely fitted, and prismatic or trapezoidal rather than strictly rectangular in shape, with several being polygonal. These, together with pillow facing on the blocks to emphasize the pattern of joints, are all Inkan characteristics (Isbell et al. 1991). In addition, some joints between large blocks in the Vinapu 1 façade are formed by the

Fig. 2.1 Detail of *Ahu* Vinapu 1 façade (author)

typically Inkan method of corner cutouts with fitted small blocks (Protzen and Nair 1997), and one block has a shaped boss, also an Inkan trait. Lastly, the façade blocks are laid in the Inkan pattern of "quasi-courses" in which, as the height of a single course is never perfectly uniform, no line of joints is strictly horizontal (Protzen and Nair 1997). The Vinapu 1 stone block thickness (0.5–0.7 m) overlaps the usual Inkan range of 0.65–1.0 m (*contra* Skinner 1955, Golson 1965). The Vinapu 1 wall batter is 12^0, which is greater than the common $3–5^0$, but still within the Inkan range of $3–15^0$ (Hyslop 1990). The façade has, understandably, no sockets cut to secure blocks with metal cramps (Protzen and Nair 1997). Overall, the intricate similarity of the Vinapu 1 façade to Inkan examples is compelling, and further underlined by the relative proximity of Easter Island to South America and an absence of comparable evidence elsewhere in Oceania.

So long as it was proposed (Heyerdahl 1952) that Vinapu 1, and *ahu* in general, had an Andean derivation in Tiwanakan culture (AD 400–1100), and while that was consistent with archaeological chronologies suggesting that Easter Island *ahu* were constructed AD 600–1100 (Martinsson-Wallin 1994: 112), then it was apparent that Inkan comparisons could not be sustained. Typical Inkan monumental stone construction is dated to around the end of the fourteenth century in the Lake Titicaca region, and Inkan authority did not extend to the Pacific coast of northern Peru and Ecuador until around AD 1430–1460 (Marsh et al. 2017) where, moreover, monumental construction was largely in adobe brick. Now that the Easter Island cultural chronology begins around AD 1200 (DiNapoli et al. 2020; Hunt and Lipo 2018), the Andean parallel comes into focus, although there are few reliable radiocarbon ages for Vinapu 1.

Excavation of Vinapu 1 disclosed three phases of its construction, with the façade and its supporting ramp in the first (Mulloy 1961a). There was no evidence that, in this early phase, the *ahu* carried any *moai* (statues), or was designed to do so. Mulloy (1961a: 105) suggested that it was simply "a gigantic open-air altar" oriented quite precisely to face the rising sun at the summer solstice (Mulloy 1961a: 94). Only one radiocarbon date from a sealed context dates this phase. It is from just above the upper surface of the first-phase ramp (Smith 1961: 394, K-523). At 440 ± 100 uncal. b.p. on unidentified charcoal it provides an uncertain *terminus ante quem* of about the early sixteenth century. An age of 730 ± 200 uncal. b.p. on human bone from a crematorium "adjacent to" Vinapu 1 (Smith 1961: 394) is even more problematic. Later excavations indicated that *Ahu* Vinapu 2 and almost certainly Vinapu 1 situated only 20 m away stand on a surface containing roots and burnt timber from clearance of the original palm forest. Charred palm nut samples date the surface to AD 1300–1440 at 2σ (Martinsson-Wallin 2004; Martinsson-Wallin et al. 2013: 409), an approximate *terminus post quem*. (The Vinapu area is discussed in further detail by Martinsson-Wallin, this volume.)

If the Vinapu 1 façade originated in the fourteenth century, it might reflect Andean monumental stone construction of the Late Intermediate Period (AD 1000–1450), such as the Cyclopean masonry at Sacsayhuaman. It is generally accepted, however, that the quite sudden rise of typical Inkan monumental construction traits around AD 1400 had antecedents among the various states and cultures that were involved in the growth of the Inkan polity AD 1100–1400, notably of Killke culture after AD 1200 (Bauer and Covey 2002), although no specific course of development has yet been traced. The Vinapu 1 façade is open, therefore, to several explanations. In ascending order of plausibility, these are, first, that it is a comparatively late, local, Polynesian innovation that converged with extraordinary verisimilitude upon Inkan forms. The conjunction of novel technical procedures and multiple details of design emerging suddenly and contemporaneously in the Oceanic island nearest to the place where they have demonstrable origins, and only there, is implausible to say the least. Second, the façade might represent Andean stone-working before AD 1400 and, third, it could be Inkan in architectural origin and age.

Amerindian influence in the singularity of the Vinapu 1 façade remains the most plausible proposition, as it has been over many years (e.g. Emory 1933; Heyerdahl 1952; McCoy 1979; Martinsson-Wallin 1994: 128; Anderson et al. 2007), even to those who saw that influence as transmitted by Polynesian voyagers (Green 2005; Jones et al. 2011). Now, it might be attributed more directly to Inkan workmanship.

2.2 *Tupa*

About 27 broadly circular structures of piled stone, 2–5 m in diameter and 2–3 m tall, called *tupa*, occur almost exclusively on the northeast and southeast coasts of Easter Island. There is no agreed definition of type although "a slab-roofed masonry tower with a very small and generally square entryway near the ground on one side" (Heyerdahl 1961a: 517) will serve. Variation in size and form (see sketches of *tupa* by Ferdon 1961: 337) does not clearly separate some *tupa* from *hare moa*, so-called chicken houses, or elliptical stone structures, as depicted by Bernizet in 1768 (Heyerdahl 1961b: 58–59). The problem of separating and characterizing the similar structures has been debated (Ferdon 1961; McCoy 1979), and it is critiqued cogently by Commendador (2005: 99–109).

Few *tupa* have been investigated archaeologically and "our understanding of these structures is vague" (Martinsson-Wallin 1994: 116). By late historical consensus, *tupa* were "turtle watchtowers", yet most are not obviously positioned to suit marine observation, and they seldom have formed access to the roof (Métraux 1940: 189; Heyerdahl 1961b: 517–519; Mulloy 1961b: 323; Arana 2014: 681). Recent consideration emphasizes a sacerdotal role (Vargas et al. 2006) or use as astronomical observatories (Edwards and Edwards 2013: 186), but although marine or celestial observation might have occurred it had no obvious need of the characteristic internal architecture of *tupa*.

Tupa have thick walls through which a narrow passage leads to an interior chamber, several metres long, of informally corbelled stone with a slab ceiling (Arana 2014: 681). The chamber was suitable only for occasional shelter, and Métraux (1940: 190) points out that there was hardly any need for that because *tupa* were located near dwellings. There are references to fishermen or priests sleeping in *tupa*, and Mulloy (1961b) found midden and domestic artefacts in an unusual *tupa* associated with a cave, but Ferdon (1961: 331) added to Métraux's point by noting, "the lack of evidence of preserved fire-pits, or fire ovens, in those [*tupa*] we observe".

The probability that *tupa* had another, and perhaps more fundamental, use can be inferred from the first historical record of them, by the Cook expedition in 1774. At this early stage of contact, Rapanui residents allowed Europeans to enter their low thatched longhouses (*hare paenga*) and explore the interiors, but as relatively few such dwellings were seen, the visitors wondered where most of the people slept. Captain Cook (Beaglehole 1961: 356) saw "vaulted houses built of stone and partly under ground" but added, "I never was in one of these". George Forster observed similarly that besides the *hare paenga*, "we observed some heaps of stones piled up into little hillocks which had one steep perpendicular side, where a hole went underground. The space within could be but very small, and yet it is probable that these cavities likewise served to give shelter to the people during night". Yet, "the natives always denied us admittance into these places" (Thomas and Berghof 2000: 307). Insofar as foreigners were concerned, it seems that *tupa* were tapu.

This may have been because they were burial sites. The earliest probable description of *tupa* as burial structures is by J.L. Palmer in 1870 (Heyerdahl 1961b: 73) who was shown *hare moa*, and doubted that they were originally hen-houses, "as some very similar [structures], but with white-washed tops, were used, we were told, for sepulture". Most burial sites on Easter Island were above ground, perhaps for fear of the deity Makemake trapping the spirit of the dead if it could not escape readily to the air (remarks of Commander Geiseler 1882 and Paymaster Thomson 1886 in Heyerdahl 1961b: 80–81, 86–88). Burial occurred often, therefore, in a range of above-ground structures from numerous piled mounds or cairns, recorded by Cook and confirmed as burial mounds by La Perouse, through *tupa* and similar structures, probably including *hare moa*, to natural caves and internal spaces or crematoria in *ahu*. As Easter Island studies concerning burial focus almost exclusively upon *ahu* (e.g. Shaw 1998), not much is known about its other contexts. Nevertheless, Mulloy's (1961a) *tupa* excavation found human bone throughout the interior deposit, with European material mixed in at the top, and his "isolated tomb" at Vinapu (Mulloy 1961a), although elliptical rather than round, has the internal structure of a *tupa* and contained an extended burial. The data are few at present, but a burial function for *tupa*, and *hare moa*, probably for people of rank (Geiseler 1883 in Heyerdahl 1997: 15), is suggested, and it has been argued persuasively for *hare moa* by Ferdon (2000).

A structural similarity between *tupa* and stone buildings with a similar name, *chullpa*, which were made and used from the twelfth to seventeenth centuries in Andean Peru and northern Chile has often been observed (e.g. Martinsson-Wallin 1994: 116), but with a reluctance to hypothesize any actual connection because they had different assumed functions. Whereas *tupa* were thought to be dwellings or observatories, "*chullpa*" in the Aymara language meant "containers in which they placed their dead" (Morales et al. 2013: 2394). It is widely assumed that Easter Island "*tupa*" is a local rendering of "*chullpa*" which might be so, but *tupa* occurs elsewhere in East Polynesian languages. There, it has meanings such as to hollow out or excavate in Tahitian, and something dried up or hard in Maori, and *tupapa'u* or *tupapaku* are the common words for corpse in Tahitian and Maori, respectively (Davies 1851: 289; Williams 1971: 455). All these terms are associated with burial, including desiccation of corpses and body parts kept above ground. The Aymara-East Polynesian congruence of term, meaning, and architecture supports the notion of a common origin, or at least a convergence of ideas and practices, but when and how that occurred remains to be investigated, a task with profound implications given that cognates of *tupapaku* occur throughout Polynesian languages.

During the period of Inca domination, AD 1450–1550, *chullpa* were large, often of dressed stone, and had decorative cornices and other features. During the preceding Late Intermediate Period AD 1100–1450 however, and especially after about AD 1200, *chullpa* were relatively rudimentary: circular, 2.0–2.5 m in diameter, domed structures of undressed stone in thick walls surrounding a chamber accessed through a narrow, east-facing entrance and passage (Hyslop 1977; Stanish 2012), very much as in Easter Island *tupa*. *Chullpa* provided above-ground burial, with mummification increasing during the Inca period (Nystrom et al. 2010) and associated ancestor veneration (Epstein and Toyne 2016), with some genetic data indicating mainly patrilineal burial across generations (Bongers 2019: 72). *Chullpa* also served to demarcate access to resources and mark territories (Bongers et al. 2012). These points are interesting and pertinent in the Easter Island context, and *tupa* generally are worth much more archaeological investigation, but the main point here is that in form, function, and age, *tupa* and *chullpa* are quite similar and have no parallel elsewhere in East Polynesia.

2.3 Birdmen

"Birdmen" figures (the gender is seldom defined) can be found worldwide, but the manner in which they are depicted is highly varied, even within Polynesia. Birdmen figures (*tangata manu*) are encountered most frequently in the rock art and portable artefacts of Hawai'i, New Zealand, and Easter Island, i.e. in the margins of East Polynesia (Barrow 1998). Early Maori and Hawaiian rock art (Dunn 1972: 11; Stasack et al. 2006) has bird-headed figures with legs and arms extended but lacking fingers and toes. Some Maori instances have feathered wings. These figures are not unquestionably human, although in form and stance they follow artistic conventions for figures that are more obviously human. Conversely, in both the older and younger Easter Island styles (Lee 1992) birdmen have characteristics not found elsewhere in East Polynesia. Most have long, hooked beaks and sometimes a gular pouch, both traits suggestive of a frigatebird model. The eyes are huge and circular, often with a pupil depicted (Lee 1992: 65–74). In some cases, the eye is also the head. Many figures are clearly shown with human hands and feet.

The typical body shape in Easter Island birdmen is flexed or crouched with a bent back and elbows almost in contact with knees. Lee (1997) is right to point out that the flexed body shape occurs commonly in Maori rock art and, although rarely, in

Hawaii, but it is also common in late prehistoric Andean art. The flexed form might reference the bundle burial tradition, common in Oceania and South America, and imply, in turn, that such figures were to be seen as ancestral. Whatever its meanings, the usefulness of the flexed body shape in inter-regional linkage of rock art depends first upon determining its Pacific dispersal, insular and continental, another task yet to be undertaken.

Many Easter Island birdmen are shown in pairs. This is not uncommon in Maori rock art, but there it involves manifestly human figures and they are shown back to back, as mirror images. These do not seem to occur in Easter Island art. The most typical pairing of Easter Island birdmen is face-to-face, often joined at their feet, hands or, less often, at the beak (Barrow 1998: 348, notes some facing pairs of bird, not birdmen, heads on Maori patu handles). In addition, Easter Island birdmen often hold a round object in their hands (Lee 1992: Plate 25; Figs. 4.48; 5.14, 21, 23, 24, 24, 40, 44; 6.8, 20), which is usually interpreted as an egg, in reference to the annual enactment of the birdman ceremony adjacent to Orongo village, where most birdmen images are recorded.

Birdman petroglyphs were made into the nineteenth century, but how early they began is uncertain. It is generally agreed that the birdman cult originated relatively late in Easter Island (e.g. Rull et al. 2018), but the chronological data are ill-defined. At ‘Orongo, where 86% of birdmen figures occur, the earliest houses date AD 1540–1600 (Lee 1992; Robinson and Stevenson 2017), but the majority of birdman petroglyphs are on rock faces nearby and they are undated. Whether the ‘Orongo village was built during, or at some time after, the establishment of the ritual site, is unknown. The older birdman style of incised depictions partially erased by those in bas-relief (Lee et al. 2015–2016) suggests some time depth. Lemaitre (2012) reports a fourteenth-century age from an engraving (non-birdman) at ‘Orongo, but the charcoal sample composition and precise provenance are not disclosed.

The closest Oceanic parallels to the Easter Island birdmen are found in coastal South America, where bird-headed human and feline figures are part of an artistic tradition extending into the Inka period (Isbell 1988: 178). There is a well-known spindle whorl from Puna Island, Ecuador, on which are incised two birdmen in the Easter Island form, placed face-to-face (Fig. 2.2). The archaeological context of this item is unknown, and examination of hundreds of spindle whorls in Ecuadorian and north Peruvian museum collections (Anderson, A., Martinsson-Wallin H., and K. Stothert, unpublished notes and images) failed to find a duplicate. Nevertheless, the depiction of two birds, or occasionally of two other figures (jaguars, caimans etc.) shown side on in facing pairs, with large, circular eyes, flexed legs and arms, and sometimes holding a rounded object is common on spindle whorls and ceramic pots, notably those of the Manteño-Huancavilca culture of coastal Ecuador, dating 1100–1520 AD, and also in the preceding Guangala culture (Ricaurte 1993; Shaffer 1985). Those cultures had a strong maritime focus (Marcos 2000).

The birdman motif is found elsewhere on the South American coast of Ecuador and northern Peru, notably at Tumbes where it is seen in the mounds (*huacas*) of Túcume, dating to the late Sican-Lambayeque culture of coastal north Peru, AD 1100–1375. Here, the birdman motif is seen in male and female forms upon rafts

Fig. 2.2 Above (left) late prehistoric Ecuadorian bead (after Shaffer 1985; Fig. 6, masked men talking) and (right), Facing pair of birdmen (after Lee 1992: Fig. 4.42). Centre: spindle whorl Puna Island (Anderson et al. 2007: Fig. 7.5). Below: Ecuadorian figure holding round object (after Shaffer 1985: Fig. A-1) and birdman holding round object (after Lee 1992: Fig. 4.48)

at sea, the male figure wearing a headpiece indicative of a deity. Around the rafts are friezes of waves expressed as anthropomorphic figures holding round objects, possibly *Spondylus* shells, which also figure prominently in the art as a whole. A small silver ornament with the birdman motif was also found during archaeological excavations at Túcume (Heyerdahl et al. 1995: 226, Fig. 177).

2.4 Evaluation

To argue that complex similarities of birdmen, *tupa*, and at least one *ahu* are shared between Easter Island and more or less contemporary material cultures in the northwest Andean region is not to imply that all of the numerous such arguments in Heyerdahl (1952) and elsewhere have comparable merit. The double-bladed "dancing paddles" of Easter Island, some shown in rock art, and ceremonial paddles or staves of very similar late prehistoric Amerindian design are plausible (Heyerdahl 1998), but reed bundle boats, megalithic human figures, carved wooden poles of human figures, and *patu* weapons occur elsewhere in the Americas and Pacific, or further afield. A thorough review of all the material culture at issue, in the light of modern archaeological and ethnological evidence, is much needed.

At present, though, the strong and apparently exclusive similarities in the eastern Pacific between *Ahu* Vinapu 1, *tupa*, and birdmen on Easter Island, and cognate evidence from Peru and Ecuador, plus a broad similarity in age, sustains the plausibility of direct Amerindian craftsmanship on Easter Island. It is worth noting also that these features have a common significance as ritual items concerned with ancestry in Easter Island and South America.

It seems unlikely, but cannot be ruled out, that innovations on Easter Island arrived with returning Polynesian voyagers as detailed memories that were then materialized with astonishing accuracy. This is, in part, a question about the relative seafaring capabilities that might have been involved.

3 Amerindian Voyaging to Easter Island?

Conventional opinion in East Polynesian prehistory takes Polynesian voyaging as the exclusive mode of interaction within and beyond the region. How secure is this assumption for seafaring in the far eastern Pacific?

3.1 Polynesian Voyaging

It is argued that Polynesian seafarers made return passages by intricate astral navigation in large, fast, double-hulled canoes which had weatherly (windward sailing) capability under the oceanic spritsail. Elsdon Best (in Johnstone 1980: 203) thought Polynesian canoes would be untroubled by sailing to America because they were “built so as to sail closer to the wind than any other craft built by man”, and Holmes (1958: 129) argued that “it is more logical to assume that [contact with South America] was made by a seafaring people like the Polynesians”. This long-standing hypothesis provides the orthodox model of cultural transfer between South America and east Polynesia (e.g. Dixon 1934; Buck 1938; Suggs 1960; McCoy 1979; Green 2001, 2005; Howe 2006; Jones et al. 2011; Kehoe 2016: 63–74).

It is based on “traditionalist” beliefs about long-range return-voyaging (Anderson 2018) that arose in the re-working and embellishment of Polynesian traditions (e.g. Best 1918; Smith 1915) at a time when Polynesians were facing demographic extinction. Their sympathetic memorialists, mainly European, produced romantic narratives of the Polynesian past which later became accepted as traditional migration history by Polynesians and Europeans alike. Yet, much about Polynesian migration that is assumed to have been in the early traditional records is, in fact, absent (Anderson 2014), including evidence about prehistoric Polynesian sailing rigs and performance, and there is a similar scarcity of archaeological data. There are alternative constructions of Polynesian seafaring.

From historical evidence primarily, it is argued that the oceanic spritsail, which had weatherly potential and has been adopted for experimental canoe voyaging, probably developed after about AD 1500, replacing the double spritsail, an ancient sailing rig with not much more than broad-reaching capability (Anderson 2000, 2008, 2018). Under double spritsail during the preceding era of island colonization in East Polynesia, seafaring would have been substantially slower, significantly confined in relation to wind directions (Goodwin et al. 2014), and much more difficult overall than it appears in modern experimental voyaging. Even with an oceanic spritsail rig, Finney (1994: 283) thought an eastward passage in mid-latitude westerlies would be "immensely difficult" and none has been accomplished in an experimental voyaging canoe, or on a raft; Eric de Bisschop's raft got to within 1300 km of Chile in 1958 before she broke up (Danielsson 1960). A direct route from Easter Island to Peru, using El Niño or winter westerlies (Green 2005), would demand more persistent wind reversals than is currently apparent, or greater windward sailing capacity than is plausible; Irwin (2011: 250) acknowledges that there is no evidence either way of weatherliness in prehistoric East Polynesian sailing.

In short, while opinions are clearly divided, traditionalist assumptions about ancient East Polynesian canoe performance, accepted without demur in Howe (2006), are at least open to question. Polynesian voyages to South America would have been very difficult, but that does not rule out the possibility of success by chance. As Irwin (2011: 255) observed, "boats, on occasion, can sail from almost anywhere to anywhere else, although the odds may be against it".

3.2 Amerindian Voyaging

Various kinds of seagoing vessels existed historically, and were depicted archaeologically, along the northwest coast of South America. The largest was the balsa raft. In debate about its possible role in transferring South American items, such as sweet potato, to Polynesia, specific objections to the sailing raft have been raised: that it had little weatherly ability, a limited range at sea through rapid absorption of seawater by its balsa logs, and that it was at the mercy of ocean currents (Lothrop 1932; Means 1942). Moreover, perhaps it was not even Amerindian in origin but delivered by Polynesians?

Taking as his model an 1825 Mangarevan sailing raft that "stands alone among the watercraft of the Pacific" (Nelson 1961: 185), Green suggested that there were once palm-log rafts in Easter Island—of which no evidence exists—and that "the idea of an ocean-going sailing raft, if not an actual vessel, was [then] taken by Polynesians to South America… [where] balsa logs were substituted for wooden ones" (Green 2001: 70). He saw this as either the initial introduction of the raft to South America or as Polynesians, having canoed to South America, then building a balsa raft to sail back home. This expression of Polynesian chauvinism requires no further comment for it simply ignored historical observation and an existing alternative hypothesis that sailing rafts were developed independently in South

America, wholly or in part (Norton 1986; Zevallos 1988: 143–168; McGrail 2001: 399).

Beginning AD 1526, the earliest Spanish observations of oceangoing Amerindian watercraft in Ecuador and Peru described large offshore rafts constructed from balsa logs, propelled by cotton sails, with up to 50 crew, and carrying cargo of up to 20–30 tonnes on long offshore passages (Sámano-Xerex 1967; Heyerdahl 1955; Sandweiss and Reid 2016: 315–317). These sources reference "the ability of the rafts to sail close-hauled to windward in remarkably effective fashion" (Doran Jr. 1971: 135). That capacity stemmed from the use of movable daggerboards, *guara*, that were pulled up or pushed down in combinations that steered the raft and operated as a keel. Ling (1970) argued that *guara* are of Asian origin which is quite possible, but the Asian evidence is modern (i.e. post-AD 1500), with the exception of unconvincing *guara* in a ninth century AD engraving at Borobudur, Java (McGrail 2001: 310) where the items in question appear to be stem and stern posts. Conversely, wooden implements which may have been *guara* occur as early as 300 BC at Ica, Peru. Some authorities regard these as digging boards or ceremonial spades (Kvietok 1987; Bruhns 1994: 285–286), but heavy examples up to 2.3 m long with top handles suited to pulling up or down are more certainly *guara* as observed historically (Emanuel 2012), and *guara* imply sailing rafts because daggerboards have no purpose without sails.

Most balsa rafts were probably constructed in Ecuador, the ecological centre of balsa (*Ochroma pyramidale*) forest distribution (Edwards 1965: 113). Balsa wood has a specific gravity about six times lighter than water, yet it is inherently stronger than pine, oak, or hickory. In addition, undried balsa logs retain substantial buoyancy for months at sea and as the lashings pull into the logs, they avoid failure by abrasion common on bamboo rafts. A pioneer species on open ground, balsa probably became especially abundant when land was cleared extensively for agriculture in the late Holocene (Anderson et al. 2007). Seagoing balsa rafts were constructed by agricultural communities for fishing and coastal trade, just as other forms of shipping developed globally during neolithic phases (Anderson 2010).

The Gulf of Guayaquil, southern Ecuador, with water navigable for 350 km inland from Puná Island, up numerous tributary rivers, may have been the locus of initial development in sailing raft technology on the Pacific coast of South America (Anderson et al. 2007). The rivers flow southwest and the principal wind direction throughout the year is to the northerly quarter. In other words, the prevailing winds are upstream, as on the Nile where northerly winds enabled vessels to go upstream under sail and downstream with sails stowed. It is to this strategic circumstance that early sailing is attributed in Egypt (McGrail 2001: 16), and it is possible that Ecuadorian sailing developed similarly.

In any event, offshore fishing for tunas and swordfish occurred in Ecuador 5000 years ago, (Currie 1995: 523), and the manufacture of shell artefacts from thorny oyster (*Spondylus* sp.), pearl oyster (*Pinctada mazatlanica*), and *Strombus* sp., all obtained historically by diving, goes back to the mid-Holocene. By the late first millennium AD, these marine shells were in high demand for ritual purposes. Rafts with *Spondylus* divers are shown in early second millennium AD ornaments from Lambayeque and in clay-plaster reliefs at Túcume and Chan Chan, on the north coast of Peru. Ever-increasing demand for *Spondylus* shell, essential for rain god ceremonies in the polities of northern Peru, stimulated substantial trading activities involving the Manteño-Huancavilca people of coastal Ecuador. Prehistoric trade between Ecuador and as far north as Mexico has been argued across a range of biota and material culture (Anawalt 1992; Marcos 1995), mortuary practice (Kan et al. 1989), linguistic traits (Smith 2003), and metalworking that occur in both areas, but rarely between. The distribution of Andean artefact types suggests movement by direct voyaging between Ecuador-Colombia and West Mexico, a distance of 2500–3000 km (Dewan and Hosler 2008; Hosler 1988).

Sailing rafts were integral to such mobility. An engineering analysis of the construction, size, strength, and durability of balsa rafts, based particularly on the technology evident in the van Spilbergen (1619) drawing, concluded that they “could feasibly measure between 6 and 11 m in length and would require two masts of heights between 5 and 7.5 m. Balsa rafts in this size range had a cargo capacity between 10 and 30 metric tons” (Dewan and Hosler 2008: 36). Furthermore, Ecuadorian rafts were capable of “making at least two round-trip voyages between Ecuador and West Mexico before they became inoperable” (Dewan and Hosler 2008: 36), by waterlogging or *Teredo* worm activity. An average sailing speed of about four knots is suggested by Dewan and Hosler (2008), supported by at least one late historical observation (Heyerdahl 1955: 257), but it seems optimistic given that *Kon-Tiki* made 1.5 knots overall, perhaps hampered by its less efficient square sail and only experimental use of *guara* (Fig. 2.3).

Neither the sailing raft hull, with its *guara* technology and absence of a steering oar, nor the sailing rig was of Polynesian inspiration. The early historical data indicate a tapering two-piece mast stepped in or through the central log of the raft, without forestay or shrouds, in which the topmast section was flexible. A triangular sail, depicted unattached to a spar on the leech, and loose-footed by van Spilbergen (1619), or with a heavy seam or possibly a light boom by Madox in 1582 (Estrada Ycaza 1973: Fig. 2.1), was made from vertically joined cotton strips and tied to the mast along the luff. The clew was fastened at or close to the deck and a running backstay to the masthead enabled the sail to be tensioned. No such system was known to Polynesians or Spaniards, nor were some other early rigs, including a cruciform sheer to which a square sail was bent, recorded in 1572 by Benzoni (1985).

In 1953, Heyerdahl trialled *guara* systematically, and found that it was possible “to tack against contrary wind, and even to sail back to the exact spot where we had set off” (Heyerdahl 1955: 264). If the sailing rafts could make an average passage speed of 2 knots, i.e. the same passage speed as Polynesian double canoes according to the most reliable historical information (Anderson 2018), then a 3000 km voyage from Ecuador to West Mexico would take a little over a month, while substantial windward sailing with long boards out into the Pacific on the return passage could involve up to five months at sea (Callaghan 2003). At 2 knots, a raft could sail before prevailing easterlies from Ecuador to the Marquesas or Tuamotus, about 5000 km distant) in less than two months, and sooner to Easter Island (3500 km distant).

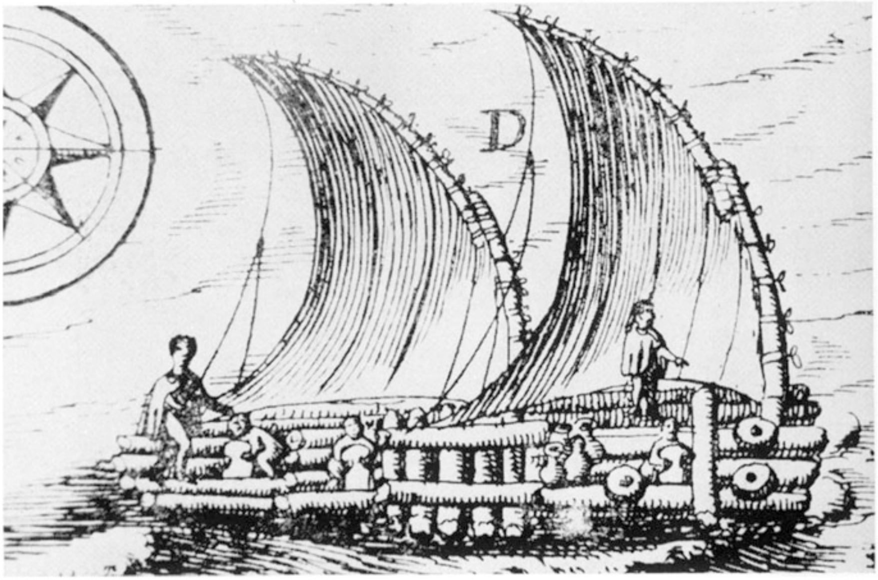

Fig. 2.3 Ecuadorian balsa raft with crescent sail rig, *guara*, and stone anchors (van Spilbergen 1619)

None of these points offer unassailable evidence of the capabilities of pre-Columbian sailing rafts, but the deep archaeology of technology transfer and trade, together with historical observations, implies strongly that a very capable, long-distance, Amerindian sailing capacity had existed for centuries before the colonization of East Polynesia.

3.3 Evaluation

Polynesian return-voyaging to South America, whether directly towards the Andean region, against prevailing easterlies, or by a prodigiously long hypothetical route involving the mid-latitude westerlies, can seldom have been successful, especially if the sailing rig prior to AD 1500 was a double spritsail. The introduction of sailing rafts from Polynesia to South America is highly implausible. In contrast, Amerindian offshore sailing rafts, their distinctive non-Polynesian sails and *guara* well-attested historically, and with an inferred offshore history longer than the human occupation of East Polynesia, were better placed to cross the southeastern Pacific. Sailing mainly in following winds, and with a weatherly capacity, the rafts were highly stable, very seaworthy, capable of long passages with heavy loads and made passages about as fast as Polynesian double canoes. More than twenty such rafting passages have been made since 1946. None of these went near Easter Island, but had *guaras* been used to hold the southeast trades on the port quarter they could have done so. Using *guara* to sail specific courses must have been part of the prehistoric maritime trading system. Without it, the Humboldt current could push a raft into the Galapagos Islands, yet there is no pre-Colombian evidence of such an occurrence (Anderson et al. 2016).

There may have been reasons for Amerindian sailing rafts to explore westward in greater numbers during the early second millennium AD than earlier. It is possible that Polynesian canoes reaching South America provided an incentive. The encroaching hegemony of the Inkan state upon the Chimu Empire and the coastal polities and trading systems of Ecuador (Volland 1995) might have been another reason for exploration westward. Indeed, the Inkan state itself, in the well-known legend about a year-long voyage of a large flotilla of rafts into the Pacific by the Inka, Tupac Yupanqui, several generations before Spanish arrival, is indicative of the notion despite its implausible discoveries.

4 Conclusions

No definitive answers can be given to the two original questions, but the balance of evidence in both cases now leans towards the Amerindian hypothesis. This reflects, firstly, the recent strong genetic indication of an Amerindian contribution, dating about the late fourteenth century, to the East Polynesian population of Easter Island. As similar genetic data, dating mainly to the thirteenth century, are widely spread in the eastern archipelagos of East Polynesia, there is a reasonable working inference that they represent the former existence of Amerindian colonists; however, those might have arrived. Secondly, Polynesian sailing to South America cannot be ruled out, but the gap between traditionalist assumptions of highly accomplished seafaring, later enacted in experimental voyaging, and the scarcity of supporting historical and archaeological data which indicates less effective technology and sailing ability recommends caution until there is greater resolution. Thirdly, it is apparent that Amerindian rafting was much more capable than is commonly envisaged in Polynesian research. In passage speed and weatherliness, it was at least a match for Polynesian double canoes, and it was more seaworthy with much greater load carrying capacity. Fourthly, updating qualitative trait comparison in the three material types considered here, together with chronological contexts, strengthens the argument that they originated in Andean South America and were taken to Easter Island. Lastly, the view that these three types were not just a random sample of quotidian or decorative items that might have been collected by visitors to South America, but are actually connected as expressions of a system of ritual behavior, makes more sense of an Amerindian landfall in Easter Island, than other scenarios. Doubtful of return, stranded Amerindian sailors may have sought pre-eminently to construct the altars, tombs, and ritual engravings that linked them correctly with their ancestors. It is also consistent with intermarriage and a weakening of Amerindian beliefs over some generations, due to which Inkan block construction deteriorated and the burial function of *tupa* was partly lost. Birdman engraving continued in a localized ritual until its *tapu* was destroyed by the liberal application of *komari* (vulvae) signs, possibly after European arrival.

It is essential to add to this re-statement that although it takes more, and more recent, evidence into account, it still lacks precise chronological controls and any quantitative analyses using large, paired (Andean-Easter Island), samples of the artefact types and styles in question. Clearly, those matters must be the next step in its evaluation. Such systematization of research has been long delayed by unwillingness on both sides of the southeast Pacific to engage with a mutual problem tainted by controversy. The easy option has been to assume that any mobility across the southeast Pacific was by Polynesian seafaring, thereby minimizing external influence in East Polynesian prehistory (Green 2005), while preserving the continentality of South American archaeology (Kehoe 2003). These tactics serve no intellectual purpose and merely validate Johnstone's (1980: 231) charge that "one thing is certain: the already vast bibliography on the question of trans-Pacific contacts will get even larger before any general agreement on the subject is reached". Instead of routine rejection of the Amerindian hypothesis, it is time to subject it to detailed analyses in archaeological science.

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Chapter 3
Commensals/Domesticates on Rapa Nui: What Can Their Phylogeographic Patterns Tell Us About the Discovery and Settlement of the Island?

Vicki A. Thomson, Michael Herrera, and Jeremy J. Austin

1 Introduction

Rapa Nui is one of the smallest, most remote, and isolated landmasses in the world to have already been settled when European explorers arrived in the eighteenth century. The first people to arrive on Rapa Nui were Polynesians thought to have island-hopped from east Asia (mitochondrial origin in southern China, Ko et al. 2014; Bellwood et al. 2017; language origin in Taiwan, Gray et al. 2009, Klamer 2019; nuclear genome origin in southern China, Yang et al. 2020) over many generations across Oceania to arrive on Rapa Nui approximately 750 years ago (Wilmshurst et al. 2011). The navigational achievements of the Polynesians simply to reach Rapa Nui, let alone persist on it, were extraordinary. Whether or not further eastward exploration included contact with pre-European South America, with accompanying gene flow between the Rapa Nuians and South Americans or only the trade of goods, is still up for debate. Either way, the transportation of animal and plant species undoubtedly proved essential to early Polynesian survival in both Near Oceania (defined as a region of the Pacific that includes New Guinea, the Bismarck

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_3

archipelago, and the Solomon Islands that was settled 35,000 years ago) and Remote Oceania (defined as the islands east of the Solomon Islands that were settled from 3000 to 3500 years ago).

Many of the animal and plant species would have been cultivated and deliberately transported by the Polynesians as domesticated species, whilst others would have been living alongside the early Polynesians, acting as scavengers, and may have inadvertently come along for the ride (e.g. commensal rats). Historical records document the range of introduced species already present when Europeans arrived in 1722, including the banana (*Musa sapientum*), bottle gourd (*Lagenaria siceraria*), chickens (*Gallus gallus*), Pacific rat (*Rattus exulans*), paper mulberry (*Broussonetia papyrifera*), sugarcane (*Saccharum officinarum*), sweet potato (*Ipomoea batatas*), taro (*Colocasia esculenta*), and yam (*Dioscorea* spp.) (La Pérouse 1797; Routledge 1919). These domesticate/commensal species, and others absent from Rapa Nui (including the dog and pig), are considered part of an 'Oceanic' package of cultural items (pottery, stone adzes, obsidian tools, shell scrapers, jewellery, fishhooks etc.), animal and plant species, and/or behavioural patterns (large settlements/villages near the shore; land clearance indicative of agriculture; long-distance seafaring) that spread from Island Southeast Asia and Island Melanesia into both western and eastern Remote Oceania (defined by a pause in settlement between 3200–2900 and 1800–1200 years ago reconstructed by language differences by Gray et al. 2009; Kirch 2000; Spriggs 2006).

By examining genetic studies of the nine animals/plants introduced to Rapa Nui by the early Polynesians, we seek to use the transportation pathways of these commensal/domesticates to reconstruct the early Polynesian migration and trade routes. Near Oceania contains multiple examples of both natural and introduced populations of cultivated plant and commensal animal species, which makes investigating human-mediated transportation pathways complicated. However, Remote Oceania lacks many of these natural populations so clearer demarcations between natural ranges and introduced populations can be made. With only two known faunal species transported by Polynesians to Rapa Nui, the differential preservation of animal bone versus plant remains in the archaeological record does create issues. Whilst the hard mineralized tissues of bone and teeth are often preserved in the environment for hundreds to thousands of years, most plant remains are quickly eroded, especially in the subtropical and tropical climates of the Pacific. Luckily, important insights about early Polynesian history can also be gained by making use of historical plant records and/or modern cultivars for the seven introduced plant species (with caveats). In this chapter, we review the current evidence from commensal/domesticate flora and fauna for reconstructing the early Polynesian migration routes prior to, and after, settling on Rapa Nui.

2 Banana (*Musa sapientum* L.)—*futi*

The banana, currently thought of as predominantly a food source in much of the world, is extremely useful for fodder, medicine, fibre, and other building materials (Kennedy 2009). The natural range of the genus *Musa* spans from Sri Lanka and eastern India in the west, across south China and Southeast Asia (SEA) to the southwest Pacific in the east and northern Australia in the south. Whilst mainly a tropical and subtropical perennial herb, the edible seedless variety of bananas common today are usually triploid, parthenocarpic (have pulp but no pollen) and clonally propagated (Jarret et al. 1992). Parthenocarpic types first arose in Near Oceania (Papua New Guinea is the epicentre of banana diversity), where the first important step of domestication was the hybridization between isolated subspecies of *Musa acuminata* (Jarret et al. 1992; Kennedy 2009). The human-mediated vegetative propagation of the seedless edible banana then occurred around the world as multiple waves stemming from slightly different hybridization events (of *M. balbisiana* and *M. acuminata,* see Fig. 3.1) (Perrier et al. 2011). By tracking archaeological remains of bananas (as microscopic starch grains otherwise known as phytoliths) we can establish that bananas were transported by Polynesians within Remote Oceania, as evidenced by their presence on Vanuatu, Hawaii, and Rapa Nui (Horrocks et al. 2009, 2017; Horrocks and Rechtman 2009). However, as phytolith evidence cannot distinguish between the multiple *Musa* species or their

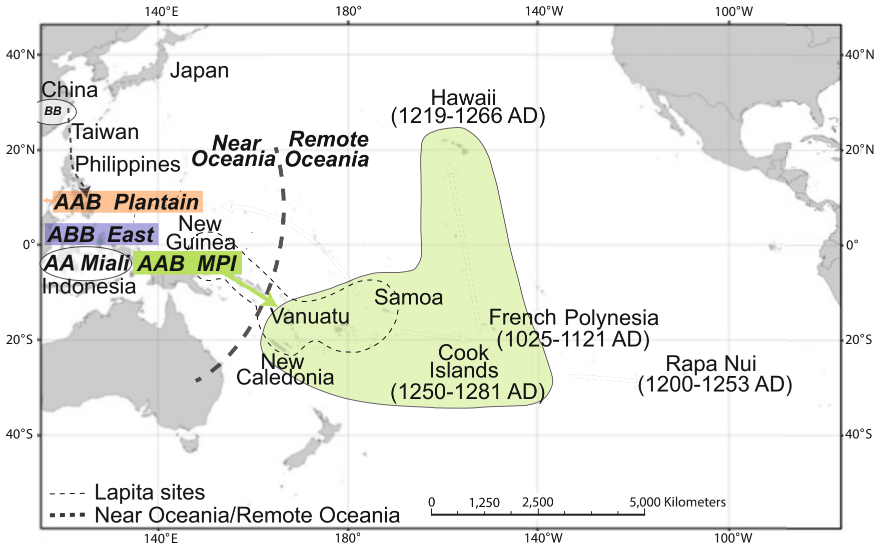

Fig. 3.1 Map showing inferred dispersal of the banana (*Musa sapientum* L.) in southeast Asia, and the Pacific (redrawn from information in Perrier et al. 2011; Kagy et al. 2016). Polynesian arrival dates noted come from Wilmshurst et al. (2011)

hybrids, genetic analysis is needed to tease apart the complex hybridization and transportation history that occurred across Oceania.

The use of genetic markers to track banana transportation into and across Oceania is complicated by its complex hybridization history including that it has occurred between different subspecies, with multiple chromosomal rearrangements and polyploidy developing (Perrier 2009; Perrier et al. 2011). By tracking the many nuclear genetic studies of bananas (which allow examination of complex genetic patterns generated via recombination), from restriction length fragment polymorphisms (RFLP; Jarret et al. 1992; Lanaud et al. 1992), isozyme analysis (Lebot et al. 1993), amplified fragment length polymorphisms (AFLP; Ude et al. 2002), and simple sequence repeats (SSR; Creste et al. 2003; Perrier 2009) to nuclear markers using Diversity Arrays Technology (DArT; Risterucci et al. 2009), we can see that banana genetics has progressed substantially in the last thirty years (Perrier 2009; Perrier et al. 2011). However, an issue common to all the domesticated plants discussed here is the assumption that modern cultivars reflect ancestral gene pools (i.e. no replacement by post-European contact gene pools has occurred), which may or may not be the case. This is further complicated by the fact that no genetic data has yet been generated from banana cultivars from Rapa Nui.

Genetic studies have shown that bananas/plantains specific to Oceania today contain both *M. balbisiana* (B) and *M. acuminata* subsp. *bansii* (A) diploid genomes (as a triploid genome represented by AAB; Perrier 2009; Whistler 2009; Perrier et al. 2011). It is proposed that Papua New Guinea (and/or the outlying islands of the Bismarck archipelago) is the likely cultivation source and site of hybridization of these subspecies that produced the triploid AAB Pacific plantain bananas in the late-Lapita occupation (Lentfer and Green 2004). The AAB Pacific plantain that was spread across Oceania by the Polynesians that is still present today includes the Maia Maoli, Popoulou, and Iholena subgroups (MPI, Fig. 3.1; Perrier et al. 2011). Although the first study using DArT had a limited geographic sampling from these MPI subgroups (Risterucci et al. 2009), a subsequent study (using only 188 DArT markers) shows enough genetic diversity is present to infer banana gene flow however it has become clear that the AAB Pacific plantains do not form a subgroup *stricto* sensu (Kagy et al. 2016). It appears the AAB Pacific plantains result from multiple triploidization events (Kagy et al. 2016).

New Caledonia appears to show the most diversity in the Pacific (multiple genotypes of intermediate AAB Maoli/Popoulou morphotypes) with the banana still imbued with great cultural significance (AAB Maoli occupy a prestigious place in family gardens and represent the identity of the clan; Kagy et al. 2016). However, further east the morphotypes are more distinct, likely due to selection at the local scale. Today, the Iholena morphotype (genetically differentiated from the Maoli and Popoulou subgroup—MP) is rare but still present as far afield as New Guinea, French Polynesia, and Hawaii (Kagy et al. 2016), suggesting all three morphotypes were transported to the extremes of Oceania by Polynesians (although no samples from Rapa Nui were included). Within the MP subgroup, a majority genotype (found in both Maoli and Popoulou morphotypes) is shared across multiple island groups, including New Guinea, New Caledonia, Vanuatu, Samoa, Cook Islands, French Polynesia, and Hawaii (Kagy et al. 2016), which makes teasing apart inter-island migration routes difficult (seen by green shading in Fig. 3.1). By using additional DArT markers or examining whole genomes across the Pacific in the future (and including bananas from Rapa Nui), the reconstruction of finer-scale phylogeographic patterns may allow us to examine the early Polynesian migration routes that transported the banana to Rapa Nui.

3 Bottle Gourds (*Lagenaria siceraria*)

The natural range of the bottle gourd across Africa, Asia, and the Americas makes identifying the origins and arrival route of the Polynesian bottle gourd difficult (Clarke 2009). However, its importance in the life of early Polynesians cannot be overstated given its potential utility in carrying water. Early molecular work suggested at least partial evidence for an Asian origin, as the chloroplast (a non-recombining plastid genome) signature was exclusively Asian whilst an American origin for the nuclear genome could not be ruled out (due to the possibility of hybridization post-European colonization; Clarke et al. 2006). Archaeological evidence indicates that bottle gourds have been present in South America since at least 7200 BP (Smith 2005) and Asia since at least 10,000 BP (Chang 1986; Gorman 1969; Habu et al. 2001), so either or both origins are plausible (Fig. 3.2). Bottle gourds are found on most of the Pacific islands, however, there is a bottle-gourd gap between Vanuatu, New Caledonia, and the Solomon Islands vs. the Cook Islands, Hawaii, French Polynesia, and Rapa Nui (Clarke et al. 2006). There is no evidence that bottle gourds were transported by early Polynesians to the intervening islands of Fiji, Tonga, or Samoa (see Fig. 3.2; Whistler 1990). This gap in bottle gourd distribution suggests that bottle gourds in the Pacific may represent two different origins, although we cannot rule out this gap resulting from the lack of wetland archaeobotanical research in this region or the use of other cultural items (e.g. pottery and bamboo) as water carrying containers negating the need for gourds to be harvested and used for this purpose.

However, the fact that experiments have shown long-distance natural dispersal (via floating) of bottle gourds with viable seeds (Whitaker and Carter 1954) is possible, suggests that human-mediated transport is not necessary to explain the arrival of bottle gourds on Rapa Nui and the other islands in Remote Oceania (see wind directions in Fig. 3.2 redrawn from Anderson et al. 2006). To examine this hypothesis further a focus is needed on generating more extensive nuclear markers for use on ancient and early herbarium samples.

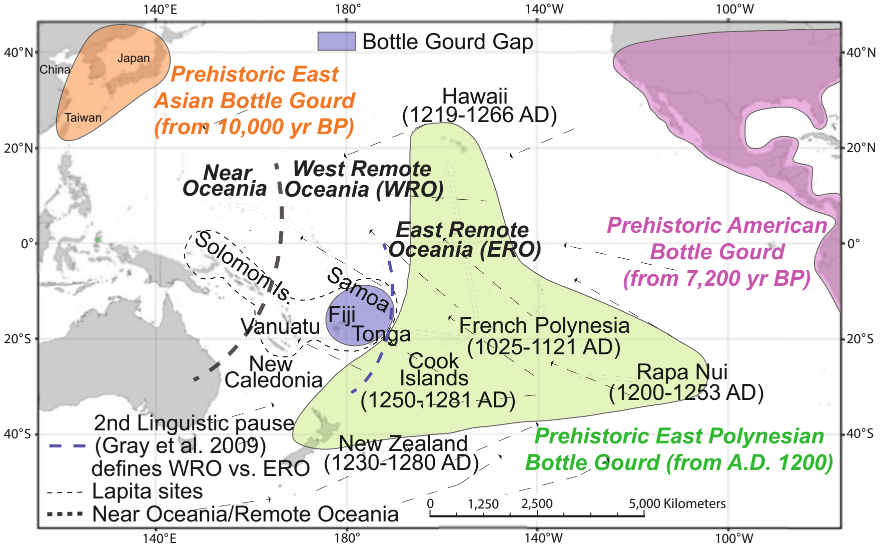

Fig. 3.2 Map showing pre-contact dispersal of the bottle gourd (*Lagenaria siceraria*) in Asia, the Americas, and the Pacific using chloroplast data (redrawn from Clarke et al. 2006 with corrected dates for earliest East Asian and American bottle gourds). Polynesian arrival dates noted come from Wilmshurst et al. (2011). The dashed arrows represent prevailing wind directions (Anderson et al. 2006)

4 Chickens (*Gallus gallus*)

The ubiquity of chickens in Oceania appears to reflect its importance as a food source, cultural artefact, and status symbol across many facets of island life. It is generally thought that chickens were domesticated first for cultural purposes in the south or southeast Asia at least 8000 years ago (i.e. for cockfighting or as items of religious significance), and only then were their meat and eggs used as a food resource (Carter 1971; Crawford 1990). However, by the time they were transported as far as Rapa Nui, separating their use in cultural practices from that as a food source is somewhat difficult; early accounts by Dutch and Spanish explorers to Rapa Nui suggest that the main medium by which social relations were initiated were largely food-related (chickens, plantains, sweet potatoes were all seen as high status and traded for European items; Corney et al. 1908:13,121; Pollard et al. 2010). As chickens appear to have been a part of the diet throughout the entire period prior to European contact, their importance as a food source is undeniable (Commendador et al. 2013).

Until recently the evidence supported domestication of modern chickens from junglefowl in northern China at least 8000 BP (Fumihito et al. 1996; Xiang et al. 2014), however, recent studies have found various issues with this theory (short DNA fragments lack enough diversity to conclusively establish the bones belonged to domesticated versus wild chickens, Peng et al. 2015; some early domesticated bird bones are actually pheasants, Barton et al. 2020). Other evidence suggests a domestication origin in southeast Asia around the same time (Fumihito et al. 1996; Liu et al. 2006; West and Zhou 1988). Subsequent work has shown that whenever or wherever the domestication process is definitively found to have occurred, it was a complex process that likely involved a red junglefowl progenitor (*Gallus gallus*), as well as grey junglefowl (*G. sonneratti*) (Eriksson et al. 2008). In fact, the most comprehensive nuclear genomic study now places the domestication origin of the chicken in southwestern China, northern Thailand, and Myanmar, a process that mostly involved the red junglefowl subspecies *Gallus gallus spadiceus* but also possibly the grey junglefowl (Wang et al. 2020).

Since this domestication, the ubiquity and easy transportation of modern chickens around the globe makes it somewhat difficult to investigate ancient phylogeographic patterns from chicken remains in the Pacific. However, unlike other species transported by Polynesians, the chicken does have clear patterns in its mitochondrial genome that reflect different migration pathways (haplogroup E was transported from India through the Middle East to Europe vs. haplogroup D, which was brought into the Pacific from Southeast Asia, Herrera et al. 2020). Whilst these different chicken migration histories can make disentangling phylogeographic patterns easier (especially by using the largely non-recombining mitochondrial DNA), the fact that modern chicken DNA can contaminate ancient chicken remains from the Pacific means that the true molecular signal can be obscured with erroneous transportation interactions being inferred (Storey et al. 2007; Thomson et al. 2014b, c). The level of diversity seen in the 201 base pairs of mitochondrial DNA sequenced in ancient samples from the Pacific already highlights some phylogeographic patterns, including a 4 base pair motif defining an Ancient Polynesian haplogroup (see Fig. 3.3, Thomson et al. 2014c). This diagnostic motif has already proved useful in further supporting a lack of pre-European contact of Polynesians with South America, as no modern chickens in South America have been found with this distinctive pattern, rather they appear descendants of European and Asian chickens (Herrera et al. 2020). The discussion around the transportation of Polynesian chickens to South America has been debated for decades, with the veracity of genetic signals and the dating of archaeological chicken bones being questioned (Storey et al. 2007, 2010, 2013; Thomson et al. 2014b, c). It may be that the only way to clarify the issue of whether chickens were transported from Polynesia to South America is the extension from short mitochondrial regions to whole mitogenomes and nuclear genomic DNA in future work (placed within the reference data now available from Wang et al. 2020). This may also provide a much more highly resolved picture of the early Polynesian chicken's translocation route to Rapa Nui.

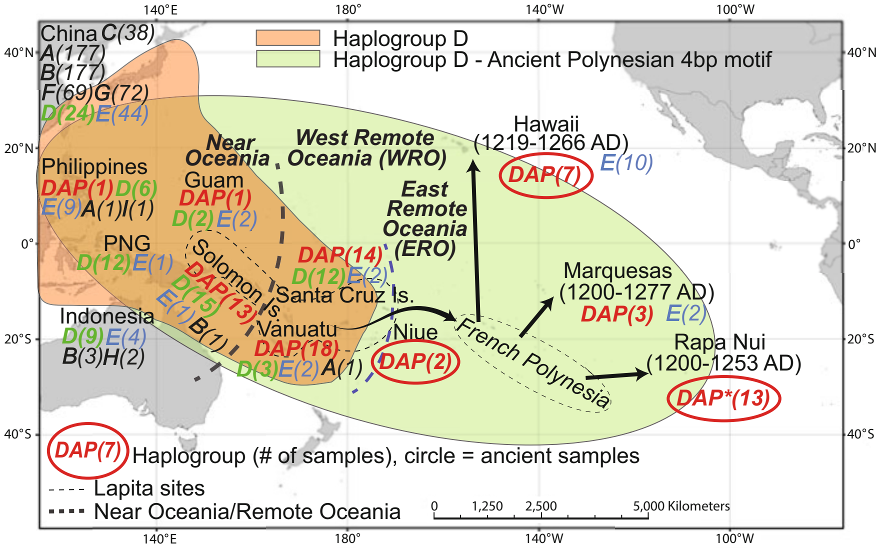

Fig. 3.3 Map showing both modern and ancient *Gallus gallus* genetic samples and authentic phylogeographic haplogroups detected within the Pacific using mitochondrial control region data (redrawn from Thomson et al. 2014c). Polynesian arrival dates noted come from Wilmshurst et al. (2011)

5 Pacific Rat (*Rattus exulans*)—*kiore*

The Pacific rat is the only other species whose faunal remains have been preserved in the archaeological record of Rapa Nui, whilst also being present widely across the rest of the Pacific (Roberts 1991). A few studies of *R. exulans* from the Pacific used morphology to distinguish Pacific Island populations (as a group) from other continental and island populations, but that is as far as cranial morphology can go with reconstructing phylogeographic patterns (Motokawa et al. 2001, 2004; van der Geer 2020). A more fruitful way of reconstructing migration patterns is by molecular genetic studies of *R. exulans* using mitochondrial DNA from archaeological and modern samples (Barnes et al. 2006; Matisoo-Smith 1994; Matisoo-Smith et al. 1994, 1997, 1998, 1999a, b, 2009; Matisoo-Smith and Allen 2001; Matisoo-Smith and Robins 2003, 2004, 2009; Thomson et al. 2014a).

The genetic studies done to date have focused on a short length (280 bp) of the hypervariable mitochondrial control region (CR) as this exhibits a relatively high level of diversity that allows some level of reconstructions of the human-mediated migration routes of *R. exulans* across the Pacific (see Fig. 3.4, Matisoo-Smith and Robins 2004). For example, a cluster of haplotypes is found in Island Southeast Asia (ISEA; Group I), with a second cluster of haplotypes found in New Guinea/Philippines (Group II), and a third cluster of haplotypes found in Near and Remote Oceania (Group III) (Matisoo-Smith and Robins 2004). Within Group

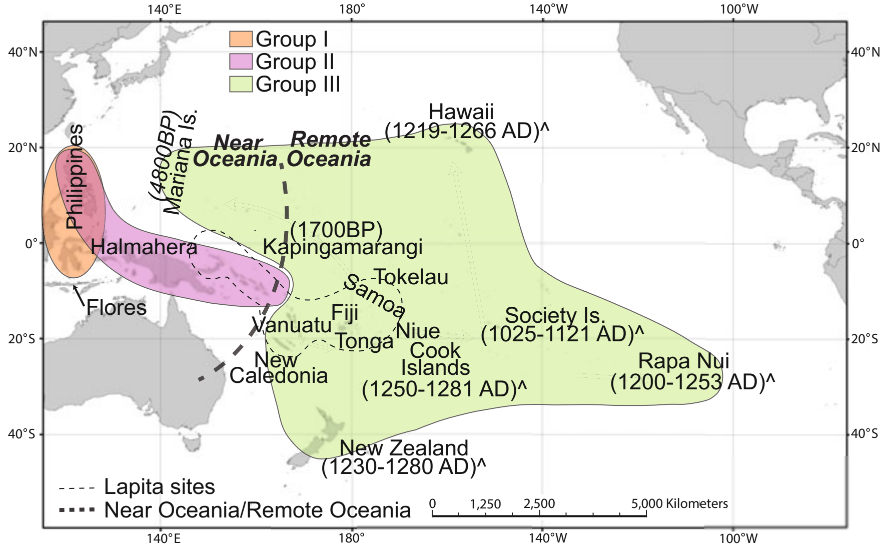

Fig. 3.4 Map showing both modern and ancient *Rattus exulans* genetic samples and phylogeographic haplotypes detected across the Pacific using mitochondrial control region (redrawn from Matisoo-Smith et al. 1998; Matisoo-Smith and Robins 2004). Polynesian arrival dates noted come from Wickler (2002), except those marked with an ^ which come from Wilmshurst et al. 2011

III, there is a set of basal haplotypes present on more central Polynesian islands (i.e. Group IIIA found on Vanuatu, New Caledonia, Kapingamarangi, Fiji, Samoa, Tokelau, and New Zealand) compared to a more derived subcluster of haplotypes found more widely throughout Oceania (Group IIIB) including at the furthest extremes in the Mariana Islands, Hawaii, Rapa Nui, and New Zealand (Matisoo-Smith and Robins 2004). However, within the Group IIIB haplotype diversity, there are no clear phylogeographic patterns to examine finer scale migration patterns between islands in Polynesia. By extending the sequencing effort to entire mitochondrial genomes and/or nuclear DNA, finer scale phylogeographic patterns may allow reconstruction of the route *R. exulans*-bearing Polynesians took to Rapa Nui.

6 Paper Mulberry (*Broussonetia papyrifera*)—*tapa* or *kapa*

The paper mulberry, although not used for food, was still one of the most widely distributed commensal plant species in the Pacific pre-contact. Its uses in making paper, barkcloth, and rope have been well documented since Captain Cook's first voyage (Whistler 2009). However, as these artefacts do not tend to preserve well in many environments, it is unsurprising that few paper mulberry remains have been found in the archaeological record in the Pacific (although a few figurines made of tapa cloth or dressed in tapa cloth were taken by early slave traders from Rapa Nui; Heyerdahl 1979; PMAE 2021). Before the development of modern genetics, little was known about the introduction of the paper mulberry to the Pacific other than that its natural range included Taiwan and southeast Asia, whilst its pre-contact/current-day distribution includes islands as far afield as Hawaii, New Zealand, and Rapa Nui (Seelenfreund et al. 2010). Although the paper mulberry is wind-pollinated, its clonal nature in the Pacific (only females are present across most of the Pacific; Penailillo et al. 2016) and the short lifespan of seeds indicates human-mediated transport and does not suggest long-distance 'natural' dispersal of seeds (Chang et al. 2015).

When examining how genetic analysis can inform us about the transportation history and route into the Pacific of paper mulberry (via their gene pool), the level of genetic variation of the region chosen is important (Seelenfreund et al. 2011). One study using the internal transcribed spacer (ITS) sequences of the nuclear ribosomal DNA region and multi-locus inter-simple sequence repeat (ISSR) markers, showed a lack of diversity on all the Pacific islands except Hawaii (González-Lorca et al. 2015). These genomic regions are therefore uninformative for identifying potential source populations of the Rapa Nui paper mulberry. When chloroplast sequences are used to reconstruct the transportation route of the paper mulberry into the Pacific they show similar patterns to those of the Polynesian chicken, suggesting that South China and Taiwan (via Sulawesi and New Guinea) are the source populations of mulberry plants found in Remote Oceania since the late 1800s, including those from Rapa Nui (Chang et al. 2015).

A more recent study using a combination of microsatellite markers, ITS-1, sex markers, and a chloroplast intergenic spacer to examine both contemporary and herbarium samples did allow the reconstruction of fine-scale translocation histories of paper mulberry across the Pacific via an Out-of-Taiwan model (Taiwan → New Guinea → Tonga → Pitcairn → Marquesas → Rapa Nui route shown in Fig. 3.5; Olivares et al. 2019), similar to the linguistic origins of the Austronesian language families (Bellwood et al. 2017; Gray et al. 2009). The work of Olivares et al. (2019) shows that the gene flow of Rapa Nui paper mulberry came from one of three dispersal hubs (Pitcairn Island) via the Marquesas. This is consistent with the rapid settlement history and long-distance trade networks amongst these islands in eastern Remote Oceania (Olivares et al. 2019). However, one caveat to these clear phylogeographic patterns is that the shared genetic signatures from Rapa Nui and Pitcairn Island found in these modern accessions may just represent the remoteness of these islands preserving the ancestral Pacific genotypes until today (i.e. the loss of ancestral Pacific genotypes from more easily accessible islands might be creating this pattern; Olivares et al. 2019). Adding more herbarium samples to this study may help refute this caveat.

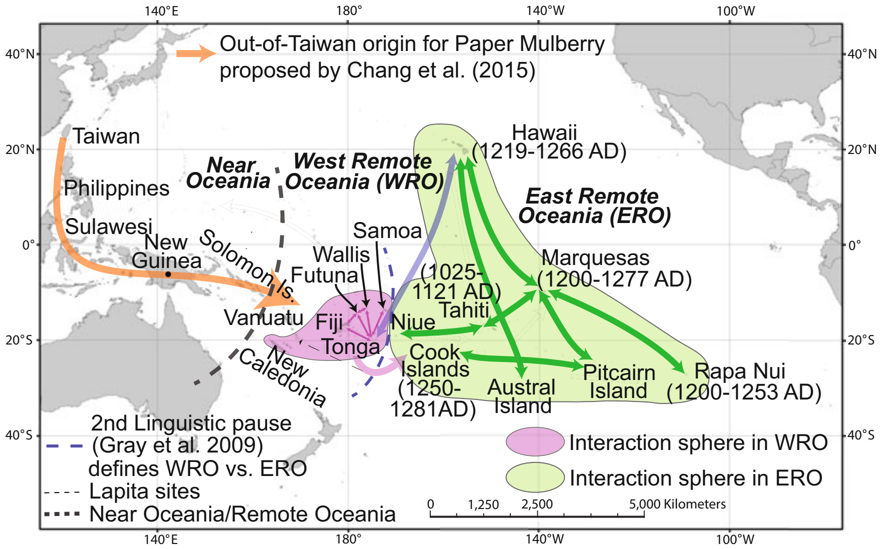

Fig. 3.5 Map showing dispersal of the Paper Mulberry (*Broussonetia papyrifera*) in southeast Asia and the Pacific using microsatellite markers, ITS-1, sex markers, and a chloroplast intergenic spacer region (redrawn from Olivares et al. 2019). Polynesian arrival dates noted come from Wilmshurst et al. (2011)

7 Sugarcane (*Saccharum officinarum*)

Sugarcane is one of the handful of important crop plants cultivated across the Pacific, but its evolutionary origin has, until recently, been obscured by the presence of wild ancestors, traditional cultivars, and modern cultivars around the world (Grivet et al. 2004). Traditionally, the molecular evidence for New Guinea as a centre of origin of sugarcane was overwhelming (as wild *Saccharum robustum*), with human domestication around 8000 BP (generating domestic *S. officinarum*) and spread into Indonesia and China where *S. sinense* was generated (via crossing and selection from *S. officinarum*) about 4000 BP and then *S. sinense* was spread into India where it became *S. barberi* (Grivet et al. 2004). Polynesians, and subsequently Europeans, spread *S. officinarum* across the Pacific from New Guinea (Grivet et al. 2004). However, more recent molecular work using whole plastid genome assemblies suggests *S. officinarum* and *S. cultum* evolved from a common ancestor, *S. robustum,* in mainland SE Asia a lot earlier, about 650,000 BP, and colonized south Asia and Indonesia between 45,000 and 20,000 BP (see Fig. 3.6, Evans and Joshi 2016). Lapita people appear to have transported *S. officinarum* to New Guinea between 6000 and 4500 BP and onwards into Remote Oceania arriving in Fiji around 1500 BP (Fig. 3.6). However, as the Pacific sugarcane cultivars (including a historical cultivar collected by Cook in 1772–1775 from the Society Islands) appear to be genetically ancestral to all modern hybrid cultivars, current

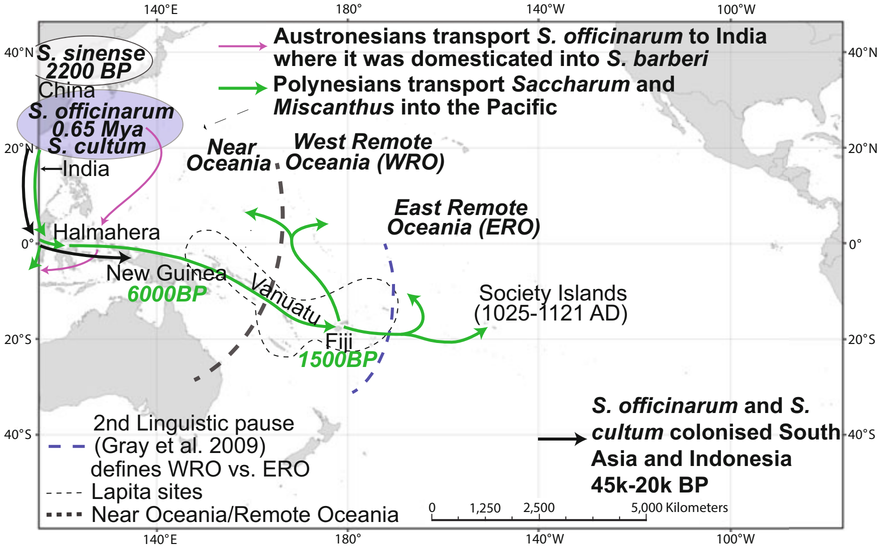

Fig. 3.6 Map showing a new model of sugarcane (*Saccharum*) origins compiled from genetic, linguistic, and archaeological evidence (redrawn from Evans and Joshi 2016). Polynesian arrival dates noted come from Wilmshurst et al. (2011)

molecular evidence can discern no clear translocation patterns within the Pacific (Evans and Joshi 2016). Future molecular work at a finer scale (i.e. nuclear genome sequencing) may offer more insight into the more complex transportation patterns of sugarcane within the Pacific to Rapa Nui.

8 Sweet Potato (*Ipomoea batatas*)—*kumara*

Starchy root and tuber crops are amongst the most important sources of carbohydrates globally and they provide a substantial part of the world's food supply, as well as being sources of processed products for human use and animal food. There were multiple types of starchy roots and tuber crops propagated by the early Polynesians as they settled on islands across the Pacific, including sweet potatoes (propagated as vine cuttings), taro (propagated as side shoots, stolons, or corm heads), and yams (propagated as tubers). These types of staple food plants had the benefit to early Polynesians of being highly adaptable to the diverse soil and environmental conditions encountered across the Pacific Islands (Chandrasekara and Kumar 2016).

The presence of sweet potato in the Pacific has been known from the early 1700s when Europeans arrived in the region. Sweet potatoes were found on all the outlying islands of the Pacific, including Rapa Nui, Hawaii, and New Zealand (Yen 1974). However, when it was discovered that sweet potato originated in the Americas, its presence in the Pacific led to speculation about how and when it arrived: was its arrival wind-directed, did the seeds float along ocean currents, were they dropped by birds (Bulmer 1966), or were they transported by pre-Columbian transpacific contact with South Americans (Thor Heyerdahl 1952; Denham 2013)?

A combination of archaeological, ethnographic, and linguistic evidence has been used to develop hypotheses about how the domesticated sweet potato was introduced to the Pacific after it became clear that its history in the region was extensive in pre-contact archaeological sites (Green 2005; Yen 1974). The most robust is the 'Tripartite Hypothesis', which tries to explain how the geographic range of three cultivars in the Pacific derive from different source populations in the Americas, where the sweet potato originates (Yen 1974). The Tripartite Hypothesis posits that the first introduction of the sweet potato (*kumara* cultivar) occurred from northwestern South America into central-eastern Polynesia in AD 1000–1100, with two subsequent events after European arrival—one in AD 1500 by Spanish traders between Mexico and the Philippines (*camote* cultivar) and the other in the sixteenth century by Portuguese traders from the Caribbean into eastern Indonesia via Europe (*batata* cultivar) (Green 2005; Roullier et al. 2013; Yen 1974). The earliest evidence supporting the 'Tripartite Hypothesis' is ethnographic: written accounts by Captain Cook and Captain Roggeveen of sweet potato cultivation in Hawaii, Tahiti, and Rapa Nui, as well as the existing herbarium specimens collected from Cook's voyage from 1768 to 1771 to New Zealand (Yen 1974). This is further supported by linguistic evidence, where the resemblance of the Quechua word *cumar* from the highlands of Ecuador to that of the Polynesian *kumara* was noted in the late 1800s (summarized by Yen 1974).

Luckily, the 'Tripartite Hypothesis' poses clear phylogeographic patterns that should be testable using genetic markers to answer the question once and for all. The earliest genetic study of sweet potato in the Pacific only used a few populations and showed that PNG populations were different from those found in the Americas (Zhang et al. 1998). More recent genetic studies using herbarium specimens seem to provide evidence supporting the Tripartite Hypothesis (Roullier et al. 2013). Using a combination of chloroplast and nuclear genes, Roullier et al. (2013) found evidence suggesting that the sole pre-contact introduction of the sweet potato likely occurred from northwestern South America (Peru or Ecuador) into Polynesia. However, newly published data contradicts this relatively recent link to South America and suggests a natural dispersal mechanism for the sweet potato into the Pacific (Muñoz-Rodríguez et al. 2018). This more extensive genetic analysis uses whole chloroplasts and 605 single-copy nuclear regions for 199 specimens of sweet potato and its closest wild relatives, to date the divergence of the sweet potato collected by Captain Cook from the Society Islands in 1769 (Muñoz-Rodríguez et al. 2018). The ancient divergence age of this 250-year-old Society Island sample and its distinct admixture pattern suggest isolation from Central and South American sweet potato varieties on the scale of hundreds of thousands of years (minimum divergence date of the 250-year-old Society Island sample from most recent common ancestor of 139,000 BP), which suggests a much more ancient arrival in the Pacific (Muñoz-Rodríguez et al. 2018).

However, there has been criticism online by some in the ancient DNA field about the fact that ancient DNA protocols were not used on the 250-year-old sweet potato sample collected by Captain Cook (Morton 2018). The DNA sequenced from this historical sample did not show DNA damage patterns (cytosine deamination at the ends of DNA strands) typical of degraded DNA, placing doubt over its authenticity. Contamination with modern sweet potato DNA and or sequencing errors may explain the divergent sequence obtained from this sample. Yet no reply to Muñoz-Rodríguez et al. (2018) has been published in the scientific literature and no retraction of the Muñoz-Rodríguez et al. (2018) paper has occurred. The last issue raised about the Muñoz-Rodríguez et al. (2018) study was the effects of calibration dates and substitution rates on their genetic analyses, but later papers have further explored the effects of these issues (Carruthers et al. 2020; Muñoz-Rodríguez et al. 2019). Without replication of the Muñoz-Rodríguez et al. (2018) study or examination of the raw sequence data, it is difficult to evaluate the importance of this study in the current discussion. Therefore, taken in its totality of genetic, archaeological, ethnographic, and linguistic evidence, the most conservative argument is that there is still doubt about whether the presence of sweet potato in central-eastern Polynesia is the result of 'natural' or transpacific human-mediated transport from South and Central America.

9 Taro (*Colocasia esculenta*)

The taro is another crop of considerable economic and agricultural importance in Southeast Asia and Oceania, both historically and in the current day. The earliest known archaeological evidence for taro consists of starch grains found on stone tools in the Solomon Islands dating to 28,000 BP but whether they reflect domesticated or wild taro cultivars is not known (Loy et al. 2015). Similar to the banana and sugarcane, taro's greatest genetic diversity in the Pacific today is found in Papua New Guinea (using microsatellite markers; Singh et al. 2007), but whether this reflects a domestication source, or is due to selection for specific agro-ecological and cultural traits by later subsistence farmers, is debated.

However, taro varieties in Indonesia, Malaysia, Thailand, and Vietnam have even more AFLP allelic diversity than PNG, suggesting that taro's origin may actually be mainland or island SEA (Lebot et al. 2004). A more recent phylogeographic study using whole chloroplast genomes (plastid) has found evidence that the taro found on Rapa Nui (Clade I) evolved in India or the Indian/Malayan region (Ahmed et al. 2020). One haplotype within Clade I has the widest distribution under cultivation (Type 1) and is found in Asia, Africa, and the Pacific, often amongst the commensal types used as food and pig fodder (Ahmed et al. 2020). But whether much of Clade I, Type 1's early dispersal was by humans is not known; it is possible that birds carried taro seeds between the mainland and islands of Southeast Asia, as is seen in wild taro in Australia (Hunt et al. 2013), before becoming vegetatively propagated. The repeated bottlenecking of taro diversity across the Pacific from west to east (see Fig.

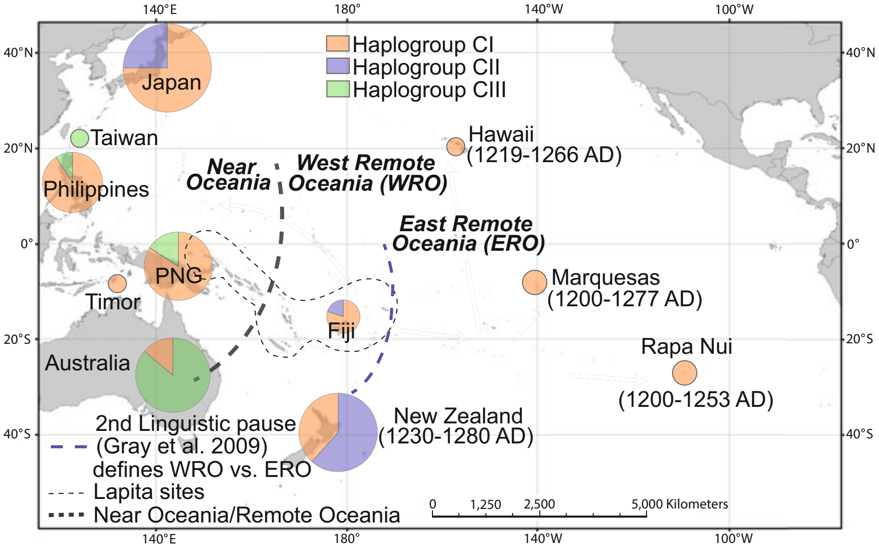

Fig. 3.7 Map showing dispersal of the Taro (*Colocasia sp.*) in southeast Asia and the Pacific using whole chloroplast genomes (redrawn from Ahmed et al. 2020). Polynesian arrival dates noted come from Wilmshurst et al. (2011)

3.7) does seem to suggest that only Clade I, Type 1 was cultivated and transported to Rapa Nui (Ahmed et al. 2020). However, further work with fine-scale molecular markers (including nuclear markers) is needed to identify the domestication origin for taro and to reconstruct its translocation route to Rapa Nui.

10 Yams (*Dioscorea* spp.)

Yams are also an important food crop in tropical and subtropical regions of the world. *Dioscorea alata* is the major cultivated species with a wide geographic distribution (Abraham and Nair 1990). *D. alata* is a sexually sterile polyploid species that is vegetatively propagated but contains accessions with various ploidy levels ($2n = 40$, 60, and 80 represent diploids, triploids, and tetraploids; Arnau et al. 2009). The origin of *D. alata* domestication is not known but based on archaeobotanical evidence it appears to have been cultivated by 6000 BP in New Guinea (Fullagar et al. 2006). This, and the fact that New Guinea is also the site of greatest *D. alata* diversity, suggests that the species was domesticated there (Lebot 1999).

The few molecular studies to date have focused on isozymes, AFLP, and microsatellite markers in modern accessions but only include samples from Vanuatu and New Caledonia (Arnau et al. 2017; Lebot et al. 1998). The samples from

Vanuatu and New Caledonia cluster together, and whilst they are relatively divergent from those from India, Africa, South America, and the Caribbean, they do include all three ploidy levels (Arnau et al. 2017). Further sampling from other island cultivars (including New Guinea) and the use of additional nuclear markers may provide more insight about how and when the different ploidy levels were generated, as well as early Polynesian transportation pathways within the Pacific to Rapa Nui.

11 Conclusion

This review of the Rapa Nui domesticate/commensal species highlights how much work is still to be done to fully explore the rich translocation history of these flora and fauna. The only domesticate/commensal with a clear translocation history published to date is the paper mulberry and some inferences about the migration routes of the early Polynesians who settled on Rapa Nui can be drawn from that. It appears that the paper mulberry follows an Out-of-Taiwan model, like the spread of the Austronesian language families, before being transported across the Pacific via New Guinea, Tonga, Pitcairn Island, and the Marquesas. However, wider geographic and temporal sampling, plus additional sequencing of plastid genomes and/or nuclear markers will be required to gain this level of detail for all the other domesticates/commensals found on Rapa Nui.

From the broad-scale phylogeographic patterns already detected, it is clear that there is still no definitive evidence for contact between early Polynesians and South/Central Americans. Whilst the sweet potato and bottle gourd are the two domesticates historically thought of as potential lines of evidence for this human contact, natural dispersal is still a possible viable explanation for their presence on Rapa Nui and elsewhere in Remote Oceania.

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Chapter 4
Sweet Potato on Rapa Nui: Insights from a Monographic Study of the Genus *Ipomoea*

Pablo Muñoz-Rodríguez, John R. I. Wood, and Robert W. Scotland

1 Introduction

Ipomoea batatas (L.) Lam., the sweet potato, is one of the most important crops worldwide and a staple in many countries. It is cultivated in warm countries for its edible storage roots, and thousands of cultivars and landraces have been recorded worldwide. It is the best-known member of the genus *Ipomoea* L., the morning glories, a group of over 800 species present in all tropical and subtropical regions of the World (Muñoz-Rodríguez et al. 2019).

Ipomoea batatas is a species of American origin (de Candolle 1883; Wood et al. 2020). Consequently, its presence in the Pacific region in ancient times has been a matter of discussion for a long time (see, for example, Clarke 1885; de Candolle 1883; von Humboldt 1825). Three possible explanations have been put forward: dispersal by natural means, transportation by indigenous inhabitants from either side of the Pacific in pre-European times, or transportation by Europeans. Currently, the leading theory combines the two latter explanations and is called the "tri-partite hypothesis" (Barrau 1957; Denham 2013; Roullier et al. 2013; Yen 1971). This hypothesis suggests the introduction of three sweet potato lineages from America into the Pacific: two independent introductions by the sixteenth century Spanish and Portuguese travellers and another, earlier introduction of a third lineage. The two European introductions are well documented (e.g. Barrau 1957; Yen 1960, 1974), although there may have been more than just two, considering the frequency of Spanish and Portuguese voyages to the Pacific from the sixteenth to eighteenth centuries (Landín Carrasco 1992).

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_4

Regarding the earlier, prehistoric arrival of sweet potato in the region, some authors have suggested it could be the result of long-distance dispersal by natural means. This hypothesis, based on a series of molecular phylogenetic analyses and computer-based modelling studies (Montenegro et al. 2008; Muñoz-Rodríguez et al. 2018; Zhang et al. 2004), has been generally dismissed in favour of a human transportation by indigenous inhabitants (e.g. Denham 2013; Green 2005). This latter theory would imply the existence of contacts between native Americans and Pacific islanders before the appearance of the Europeans. However, support for a human-mediated introduction of sweet potato in the Pacific is fragmentary and consists mainly of indirect evidence, such as that obtained from the analysis of human genetic data (Iaonnidis et al. 2020).

Answering this question—how and when did sweet potato arrive in the Pacific?—demands a critical evaluation of all evidence available. Certain disciplines, such as archaeology and linguistics, have had the predominant role so far. In contrast, the botanical evidence has been often neglected (Yen 1960, p. 368). Our aim is to help fill that gap by assessing the existing evidence from a botanical perspective. In line with the theme of this book, we specifically investigate the presence of sweet potato on Rapa Nui, although our findings may be valid for other territories. This study benefits from the experience we have gained with our monographic study of the morning glories worldwide (Muñoz-Rodríguez et al. 2019; Wood et al. 2020).

It is not our intention to deny the importance of sweet potato for Pacific societies in historic times, a topic extensively discussed by other authors (Coil and Kirch 2005; Handy 1940; Kirch et al. 1995, 2004, 2005; Ladefoged et al. 2005). However, we think it necessary to draw attention to several issues that may complicate the interpretation of existing evidence and lead to erroneous conclusions. First, publications that address the arrival of sweet potato in the Pacific are prolific in detail but, with a few exceptions, are rendered confusing by speculation. For this reason, we restrict our text to the botanical analysis of existing evidence and endeavour to minimise speculation.

Secondly, many authors simply repeat information published elsewhere without criticism; there are relatively few original works. For this reason, we attempt to highlight documents that provide original information, although we also cite some more general studies and reviews for their relevance.

The third and final issue is perhaps the most relevant. In almost all cases, evidence used to support the presence of the sweet potato is ambiguous as it could equally be used to explain the presence of other *Ipomoea* species recorded from the area. We believe a botanical perspective, often overlooked, is necessary for the analysis of the available data and will contribute to understanding the history of the presence of sweet potato in the Pacific.

2 Sweet Potato in Rapa Nui Literature

2.1 Eighteenth Century: First European Mentions

Jacob Roggeveen commanded the first European visit to Rapa Nui, in 1722. An account of that voyage, *Histoire de l'expedition de trois vaisseaux* . . . , was written by Carl Friedrich Behrens, a member of Roggeveen's crew. In his narrative, Behrens explained that different roots were eaten by Rapa Nui inhabitants, but there is no explicit mention of the sweet potato either in the German (Behrens 1738) or in the French (Behrens 1739) versions of the text. The first mention of the roots by Behrens ("red and white roots")[1] could refer to sweet potatoes but also to other root crops, and he explicitly mentions potatoes (*pommes de terre*). In addition, four pages later Behrens explains that these roots taste "almost like bread"—a description that we think does not really fit that of the sweet potato, often described as having a chestnut taste—and that islanders used them *instead of* bread.[2,3] Behrens could be referring to sweet potato but also to yams of the genus *Dioscorea* (Hahn et al. 1987; Martin et al. 1974b), to taro, *Colocasia esculenta* (L.) Schott., or even to manioc, *Manihot esculenta* Crantz (Blixen 1977; Langdon 1998; Mellén Blanco 1986).[4] On the same trip, Roggeveen's logbook reads: "[. . .] *we found it* [the island] *not only not sandy but on the contrary exceedingly fruitful, producing bananas, potatoes, sugar-cane* [. . .]" (Corney 1903a, p. 21). Again, Roggeveen's use of the term "potatoes" may refer to sweet potato or may have been used as a general term for several different root crops.

Almost five decades passed before the next European visit to Rapa Nui. In 1770, a fleet commanded by the Spanish Felipe González de Ahedo arrived on the island

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[1] *Nous fimes aussi-tot tous les preparatifs pour la descente, mais avvant que de l'exécuter l'Insulaire que nous vions reçû à notre bord deux jours auparavant, vint une seconde fois accompagné de plusieurs autres, nous apporter une grande quantité de poules et* ***de racines aprêtées et accommodées à leur manière*** [. . .] (p. 126).

[2] *Comme ils virent par-là, que notre dessein étoit de les traiter en amis, ils nous rapporterent un peu après encore cinq cens poules, toutes en vie. Ces poules ressemblent à celles de l'Europe.* ***Ils les avoient accompagnées de racines rouges et blanches, et d'une grande quantité de pommes de terre, dont le goût est à peu près comme celui du pain, aussi ces insulaires s'en servent ils à sa place*** [. . .] (Behrens 1739, pp. 129–130)

[3] (Skottsberg 1922, p. 62) attributes a specific mention of the sweet potato to Behrens: "Bataten, die wie Brot schmeckten". We were however unable to find this sentence in the 1738 edition of Behrens' text. A later version of Behrens' text, apparently extensively modified by the editor, was published in Leipzig almost two centuries later, in 1923 (Behrens 1923). As precisely shown by Zuzanna Jakubowska, the editor of the 1923 edition incorporated many changes of his own without indicating these, including one or more specific comments about sweet potato absent from the 1738 edition (Jakubowska 2012, p. 26). We refer the reader to the works of Zuzanna Jakubowska for further details on this question.

[4] We refer the reader to the works of Langdon (1998) and Mellén Blanco (1986) for more on the possible presence of manioc, *Cassava esculenta*, and of other crops in the Pacific islands in ancient times.

to map the territory and to claim it for the Spanish Crown. An account of that trip was probably written by officer Juan Hervé (Corney 1903b, p. 113; Mellén Blanco 1998, p. 208) and is readily available in an early-twentieth century translation by Bolton G. Corney (1903b). According to Corney's translation, Hervé recorded that the sailors received from islanders "*plantains, Chili peppers* [sic]*, sweet potatoes and fowls*"[5] (Corney 1903b, p. 121), and islanders had "*several plantations and fields of sugar-cane, sweet potatoes, taro, yams* [. . .]"[6] along the coast (Corney 1903b, p. 123). By the time González de Ahedo arrived at Rapa Nui, the Spanish had ruled in America for almost two centuries and it seems plausible that they would be able to differentiate between sweet potato (*camote*), manioc (*yuca*), and other roots they came across (Langdon 1998; Mellén Blanco 1986, 1998). To the best of our knowledge, Hervé's text is the first indisputable mention of sweet potato on Rapa Nui.

In 1774, 4 years after González de Ahedo, James Cook arrived on Rapa Nui as part of his second voyage to the Pacific (1772–1775). Cook's crew included naturalist Johann Reinhold Forster and his son, George Forster, both of them authors of relevant accounts. Sweet potato is mentioned several times in *A voyage round the world,*[7] attributed to the son (Forster 1777), and also in a French manuscript recently found in Poland attributed to the father[8] (Jakubowska 2014). Perhaps surprisingly, George Forster did not mention the species in his *Florulae insularum Australium Prodromus* a few years later (Forster 1786), although other important species recorded in the narratives of Cook's voyage are also missing from George Forster's

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[5] "[. . .] *platanos guineos,* ***camotes*** *y gallinas, y los nuestros les dieron sombreros, chamarretas, etc.*" [from Mellén Blanco 1998]. It has been noted that Corney's translation of Hervé's text includes some inaccuracies and omissions concerning the names of cultivated plants (Langdon 1998; Mellén Blanco 1986), so it should be read with some caution. Note the Spanish document, for instance, does not mention Chili peppers, as pointed out also by Mellén Blanco (1986) and Langdon (1998, p. 326). The text by Hervé indisputably mentions sweet potatoes (*camotes*).

[6] "[. . .] *caña dulce, camote, yuca, ñame, calabaza blanca y mates de los que en el Callao sirven para lastrar*", from (Mellén Blanco 1998). Note the translation by Corney has "taro" but the original in Spanish says "yuca", two different crops.

[7] *The potatoes were of a gold-yellow colour, and as sweet as carrots, therefore not equally palatable to us all; however they were extremely nourishing, and very antiscorbutic* (Forster 1777, p. 572). [. . .] *We now embarked with a small quantity of potatoes, and with . . .* (p. 576). [. . .] *We followed one of the paths which the natives had made, till we came to a cultivated spot, consisting of several fields planted with sweet potatoes, yams, and eddoes, together with a species of night-shade . . .* (p. 578). [. . .] *who brought him* [Captain Cook] *some fowls ready dressed, and some matted baskets full of sweet potatoes, but sometimes deceived him by filling the basket with stones, and only laying a few potatoes at the top* (p. 579). [. . .] *A field of sweet potatoes was situated close to the well, and a considerable number of people of different ages and sizes, busied themselves in digging them up, and bringing them for sale to our people* (p. 582), etc.

[8] *Soleil il ne laisse cependant pas de devenir extremement fertile par la culture, et comme l'île n'est pas à présent très peuplée, il y a tant de terre en friche, qu'un jeune homme qui a envie e faire menage à part n'a qu'à occuper un terrain, à le defricher avec un instrument de bois dur, de la figure d'un pieu pointu, dont on se sert u lieu de bêche, ses parens & ses amis ne lui refusent pas quelque* ***racines de batates*** *qu'on coupe à chaque bouture pour les multiplier* [. . .]

Prodromus (Skottsberg 1953, p. 61). More importantly, the two aforementioned narratives include up to 15 mentions of the sweet potato in the text, and Johann Forster specifically describes the crop as "profusely cultivated in one of the coasts".

In summary, there is no doubt that the sweet potato was already widely cultivated on the island by the time González de Ahedo and Cook visited Rapa Nui, in 1770 and 1774, respectively. The documents we consulted pertaining to Roggeveen's visit 50 years earlier are compatible with the cultivation of the crop on the island in the early eighteenth century, but do not demonstrate it conclusively.

2.2 Nineteenth and Twentieth Centuries: Sweet Potato as a Staple

In the nineteenth century, sweet potato was an important element of the islanders' diets. Eugène Eyraud, the first Westerner to live on Rapa Nui (in 1864 and 1865–1868), seemed to eat sweet potatoes very often[9] (Eyraud 1866). Further, the importance of sweet potato in the island economy is obvious in all subsequent works (e.g. Díaz Vial 1947; Métraux 1957; Yen 1974). Alfred Métraux, for instance, made it clear that sweet potatoes were the main staple on the island in the twentieth century:

> An Easter Islander who wished to give me an idea of the monotony of life on his island once said to me: 'Here, we are born, we eat sweet potatoes, then more sweet potatoes, and then we die'.
>
> (Métraux 1957)

In the early twentieth century, the Chilean scientist Francisco Fuentes cited by their names two varieties cultivated by the islanders ("camote morado" and "camote negro"), and two more varieties in passing[10] (Fuentes 1913, p. 335). The names "camote morado" and "camote negro" are also used for traditional Peruvian and Central American landraces (http://genebank.cipotato.org), but we cannot say whether this indicates a relationship (i.e. they are modern American cultivars recently introduced) or is pure coincidence.

Considering the importance of the crop, it is not surprising that islanders developed and grew several varieties even on a small island the size of Rapa Nui, such as the 4 recorded by Fuentes, although perhaps not as many as the 11 different varieties reported by Douglas Yen (1974). It is interesting that Fuentes did not mention any white-fleshed varieties, whereas by the end of the twentieth century

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[9] *On a bientot cuit les éternelles patates: c'est le plat de tous les jours, l'invariable ordinaire des Kanacs, grands et petits.* Note Eyraud refers to the crop as simply *patates*. It has been assumed by previous authors that this refers to sweet potato and not to the Andean potato, *Solanum tuberosum* L.

[10] *Hai* [sic] *otras dos especies o variedades de camotes.*

at least one of two types of sweet potatoes in cultivation on the island had white flesh (Aljaro et al. 1999). The varieties described by Aljaro et al. (1999) may or may not represent different varieties from those recorded by their predecessors. Of course, the island has changed dramatically before and during the two centuries after the first European contact (Horrocks et al. 2013; Métraux 1940; Rull 2020; Yen 1974). It is definitely possible that the original indigenous sweet potato varieties were replaced by other, more productive American varieties in the nineteenth and twentieth centuries.

3 The Morning Glories of Rapa Nui

As explained above, *Ipomoea batatas* is the best-known member of the plant genus *Ipomoea*, but it is not the only species recorded in the Pacific nor on Rapa Nui. Several other species have been recorded in the Pacific region (Muñoz-Rodríguez et al., *in prep.*). Most of these species have a widespread distribution; they are found across the Ocean and often both in Asia and in the Americas, and some may be relatively recent introductions to the Pacific region. Several species apart from sweet potato are eaten by humans, and some are also used for their edible storage roots (Muñoz-Rodríguez et al. 2019).

The eighteenth and nineteenth century floristic accounts of the Pacific islands did not record any *Ipomoea* or Convolvulaceae species on Rapa Nui, apart from sweet potato. Neither the first known floristic work to include Rapa Nui, by George Forster (1786) nor Endlicher's (1836) "*Bemerkungen über die Flora der Südseeinseln*", nor Hemsley's (1885) *Report on the present state of knowledge of various insular floras* mentioned any other species of the genus or the family on the island. These works were compiled as a result of long expeditions focused on a much larger area than Rapa Nui, so the fragmentary compilations, considering the nature of those voyages, may not be surprising.

The first more or less complete floristic work focused on Rapa Nui was carried out by Chilean botanist Francisco Fuentes. Fuentes visited the island as a member of Walter Knoche's 1911 scientific expedition and published two reports, one in Spanish (Fuentes 1913) and another one in German—as a chapter in Knoche's *Die Osterinsel*. Knoche's book was first published in Chile in 1925 and has been recently reprinted (Fuentes 2015). Fuentes recorded approximately 135 species of plants native to Rapa Nui and is the first author to record other species of Convolvulaceae from Rapa Nui apart from sweet potato. Fuentes' narratives, however, are contradictory and difficult to interpret. He, for example, cites different Convolvulaceae species in the two documents even though both refer to the same expedition. The one species Fuentes recorded in both works is the pantropical species *Ipomoea pes-caprae* (L.) R.Br. (Fuentes 1913, 2015).[11] *Ipomoea pes-caprae*, the goat's foot morning glory, is a species from sandy coasts in tropical and subtropical regions, and a pioneer on newly formed oceanic islands. This species is easily recognised by its characteristic leaf shape, hence its common name (Devall 1992; Wood et al. 2020). Importantly, the roots, stems, and leaves of this species have been eaten as a famine food in Rapa Nui (Métraux 1940, p. 160; Orliac and Orliac 1996, p. 94) and elsewhere in the Pacific (Neal 1965, p. 709; Chock 1968).

In addition to *Ipomoea batatas* and *I. pes-caprae*, Fuentes (1913) mentioned two other Convolvulaceae species—*Ipomoea kentrocaulos* C.B.Clarke (now a synonym of *Distimake kentrocaulos* (C.B.Clarke) Simões & Staples) and another, unnamed species—but apparently the specimens collected were lost before the preparation of his work and no other information exists. The records by Fuentes remain unconfirmed.

In his work in German, Fuentes does not mention any of the species in the previous paragraph but does include *Ipomoea fastigiata.*[12] This name is now considered a synonym for *I. batatas* (Wood et al. 2020 pp. 394–395), although many authors in the past cited it as a synonym of another sweet potato relative—*I. tiliacea* (Willd.) Choisy. Fuentes succinctly describes *I. fastigiata* as "schwarze Camote" (camote negro, black sweet potato), and a few pages later Knoche (p. 131) records "two types of bulbs, *I. batatas* and *I. fastigiata*".[13] They possibly referred to the "camote negro" sweet potato variety mentioned in Fuentes' 1913 work (see previous section), but it is unclear why he would assign the same entity, observed on the same trip, to different species in different works and with no explanation.[14] Finally, the Chilean botanist also noted that many foreign plant species had been introduced

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[11] It is curious that Ipomoea pes-caprae was not recorded by the eighteenth-century naturalists such as George Forster, even under the name *Convolulus pes-caprae* or another synonym. It is more difficult to understand that this widespread pantropical species was not mentioned by subsequent authors in the nineteenth century such as Endlicher or Hemsley.

[12] Fuentes did not provide authorship for this name, but here we assume he referred to *Ipomoea fastigiata* (Willd.) Sweet, now a synonym of *Ipomoea batatas* (Wood et al. 2020 pp. 395–396). Apparently, Chapman used the name *Ipomoea fastigiata* to describe a different entity that is now a synonym of *Ipomoea indica* (Burm.) Merr., but Chapman's name has never been used since its publication.

[13] Knoche adds: "Letztere ist im tropischen Amerika heimisch, während die Heimat der ersteren wohl in Hinterasien zu suchen ist." (The latter is native to tropical America, while the home of the former is likely to be found in Western Asia). Previously some authors thought the plants cultivated in America and in Asia belonged to different species, but it was later agreed that they both were, indeed, *Ipomoea batatas*.

[14] We can speculate further about the identity of this species. If by *Ipomoea fastigiata* Fuentes referred to a species of *Ipomoea* other than sweet potato, no such species has been recorded by subsequent authors and may thus have become extinct since then. Alternatively, if this was a form of sweet potato, why would Fuentes record it under a different name? Were these plants growing in the wild and, if so, were they native or escaped from cultivation? We requested information from the Chilean Museo Nacional de Historia Natural, where Fuentes' collections were deposited, but apparently no specimen under this name has been preserved. In the end, this question may never be successfully answered.

to Rapa Nui in previous decades and were now widely cultivated (Fuentes 1913 pp. 324–325, 2015 pp. 121–122), something that has further complicated the identification of truly native elements ever since.

More recently, the *Catálogo* by Rodríguez et al. (2018) recorded *Ipomoea pes-caprae* as native to Rapa Nui but did not mention *I. batatas*, probably because of its cultivated status.

Two other Convolvulaceae species have been recorded from Rapa Nui: *Calystegia sepium* (L.) R.Br. (Skottsberg 1922) and *Jacquemontia paniculata* (Burm.f.) Hallier f. (Zizka 1991). In neither case was a specimen retained nor have the plants been found again so their occurrence in Rapa Nui is doubtful in the extreme.

In conclusion, there have been just a few botanical studies on Rapa Nui, and they are difficult to interpret due to the varying levels of detail and accuracy. Only two species of Convolvulaceae have been recorded with certainty in the territory in the last centuries: *Ipomoea batatas* and *I. pes-caprae*, with the references to other species probably a mistake. The relatively low number of species recorded on the island is not surprising, given its remoteness and small size.

4 Sweet Potato in the Archaeological Record

Archaeological remains assigned to sweet potato on Rapa Nui consist mainly of charred specimens, pollen grains, and starch grains (Fig. 4.1). As on other islands, many authors before have discussed the presence of sweet potato on Rapa Nui in ancient times, but most references provide no direct supporting evidence. A chronological review of archaeological records supported by direct biological evidence (remains of plant origin) is provided below, whereas indirect evidence—structures such as walls or pits (e.g. Stevenson et al. 2006), as well as oral traditions and legends (Best 1925; Heyerdahl 1952; Wallin et al. 2005)—is beyond the scope of this chapter and is not discussed.

In 1961, Arne Skjølsvold reported the discovery of charred remains in a fireplace at Anakena, on the north coast of the island (Skjølsvold 1961). Some of those remains were identified as sweet potatoes, although Skjølsvold did not provide an explanation for the identification.[15] C^{14} dating of carbon samples from the lower part of the oven, besides the fireplace where the charred remains were found, resulted in a date of 1526 AD ± 100 years.

Wallin et al. (2005) and Horrocks et al. (2012a,b) cited two publications by Catherine Orliac (Orliac and Orliac 1998a; Orliac 2000) reporting sweet potato tuberous root remains associated with late prehistoric ovens. The 2000 publication is an excellent summary of vegetation changes on the island over 35,000 years,

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[15] [The remains] *could be identified as the remains of sugar cane, sweet potatoes, and a small, nut-like fruit* (Skjølsvold 1961, p. 297) [. . .] *Charred sweet potatoes were also discovered* (p. 297) [. . .]

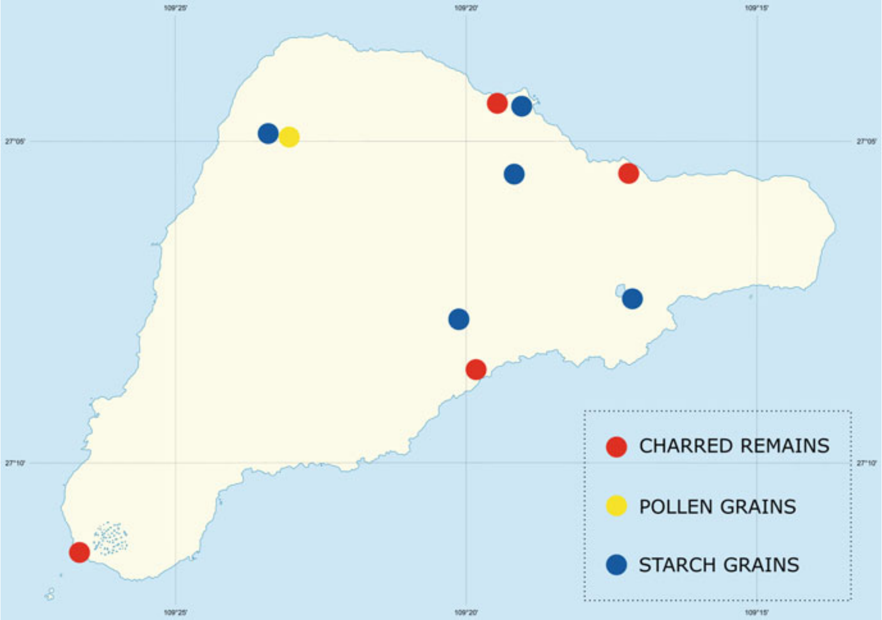

Fig. 4.1 Location of archaeological remains identified as sweet potato on Rapa Nui. Basemap by Eric Gaba (Sting), derivative work: Xfigpower (pssst) (CC BY-SA 2.5, https://commons.wikimedia.org/w/index.php?curid=12178573)

but there is no mention of sweet potato (Orliac 2000).[16] Orliac's 1998 publication is a contribution to an international conference, and the reference to sweet potato is in fact a note to another, earlier report edited by Chaterine Orliac and Michael Orliac with plant remain identifications by Erik Pearthree (Orliac and Orliac 1996). According to this 1996 report, at least 20 specimens from different parts of the island were identified as *Ipomoea* remains (Fig. 4.2). Identification of plant remains in that study was conducted by comparing the remains with charred samples of plants cultivated in Polynesia, including starchy food plants. The author does not explain the specific traits that enabled the identification of *Ipomoea batatas* remains, although an image kindly provided by Catherine Orliac of one of the specimens collected at Orongo resembles sweet potato with little doubt (Fig. 4.2). This is a recent specimen though, being found in an archaeological level dated 030 +/−80 conv. BP, calibration 2-sigma 1675–1775/1800–1945, (Orliac and Orliac 1998b, p. 5) and thus does not help clarify when sweet potato arrived on the island.

In terms of micro-remains, these have been found at Ahu Te Niu and La Perouse (Horrocks and Wozniak 2008); Rano Raraku (Horrocks et al. 2012a); and

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[16] The author mentions the existence of hundreds of plant remains, most of them charcoal fragments of a few millimeters, but does not mention sweet potato.

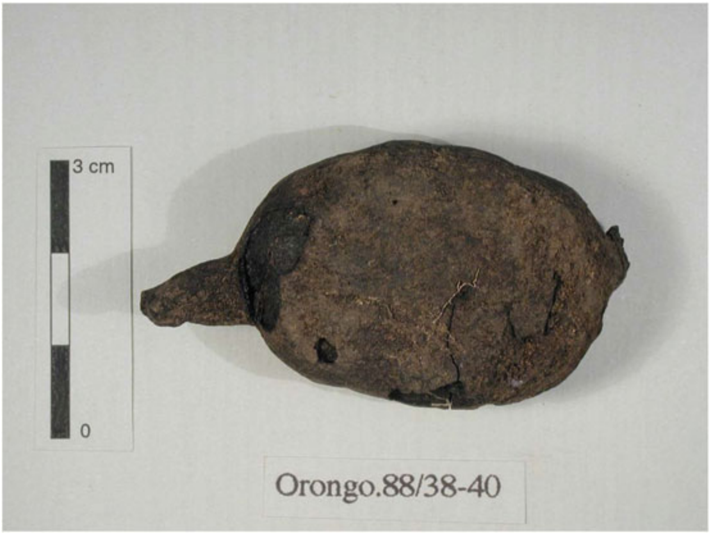

Fig. 4.2 Charred root from Orongo site (SW Rapa Nui) identified as sweet potato from Orongo site. Photograph by Catherine Orliac

Kaovaokiri, Vaitea Atroke Hau, and also Rano Raraku (Horrocks et al. 2017) (Fig. 4.1). We found no mention of *Ipomoea* remains in studies at Rano Aroi (Flenley 1979; Flenley et al. 1991; Flenley and King 1984; Horrocks et al. 2015; Margalef et al. 2013; Margalef Marrasé 2014; Peteet et al. 2003; Rull et al. 2015) or Rano Kau (Flenley 1979; Flenley et al. 1991; Flenley and King 1984; Horrocks et al. 2013).

Publications by Horrocks and collaborators are remarkable in that they provide detailed descriptions of their findings, explain the basis for the identification of the material and discuss the possibility that some of the remains belong to wild plants, which is certainly possible. Their first study described sweet potato starch grains from Ahu Te Niu and two other sites, 200 and 900 m to the east of Te Niu, respectively (Fig. 4.1) (Horrocks and Wozniak 2008). The starch grains are described as large (up to 25 μm in diameter), ovate to sub-triangular and a vacuole at the central hilum (Horrocks and Wozniak 2008, p. 134), and appeared in all samples studied except the two oldest ones. According to the authors, individual sweet potato starch grains would constitute the second most abundant type of grain after those of *Dioscorea alata*, which predominate in the samples.

In the study at Rano Raraku, Horrocks et al. (2012a) found pollen fragments (see Figs. 6a and 7a in Horrocks et al.'s paper) and starch grains in two cores, one from a lake sediment and the other from dryland soil. Based on a previous review (Cummings 1998), the authors argue that the pollen grains of *I. batatas* and *I. pes-caprae* can be differentiated, thus classifying their finding as *I. batatas*. Cummings (1998, p. 102) explains that the *I. batatas* pollen can be distinguished by the "densely packed rods that form the shape of a coarse reticulum around each pore", a feature not observed in *I. pes-caprae*.

5 Analysis of Archaeological Remains from a Botanical Perspective

Botanical knowledge, often missing in sweet potato studies, may help interpret archaeological remains associated with sweet potato. To conclude this chapter, we would like to discuss in more detail the archaeological remains identified as *Ipomoea batatas* on Rapa Nui from a botanical perspective. Generally speaking, how *Ipomoea* archaeological remains are identified is an important issue. Except in some exceptional, detailed studies, authors do not mention the criteria they used to identify their findings as sweet potato (e.g. Skjølsvold 1961), which makes discussion impossible. Further, it is difficult to know with what degree of confidence the authors were able to differentiate between cultivated sweet potato and other *Ipomoea* or Convolvulaceae species. In fact, the similarity of both macro- and micro-remains with those from other closely related taxa (see, for example, photographs in McCormick 1916; Sengupta 1972; Wilkin 1996; Eserman et al. 2018) generates doubts not only among us, but also among other authors.[17,18] Consequently, some remains identified as sweet potato have later been re-identified as wood charcoal or as belonging to other species (Coil and Kirch 2005; Patterson and Lanning 1964, 1966).

To the best of our knowledge, only two studies have reported sweet potato macro-remains on Rapa Nui (Orliac and Orliac 1996; Skjølsvold 1961). The discovery by Skjølsvold is difficult to assess, since, as explained earlier, the author did not provide any information or pictures to allow further investigation. Another problem affecting these remains is that only a single radiocarbon date was provided (1526 AD ± 100 years). According to Wallin et al. (2005), a single radiocarbon date does not represent the timespan in which a place was occupied nor allows us to link this to the date when the sweet potatoes were burnt. The identification of the remains reported by Skjølsvold, even if correct, may be of limited value without a broader context. On the other hand, the remains reported by Orliac and colleagues are more compelling. They report up to 20 specimens from three different locations on the island. Nonetheless, the authors did not explain the basis for the identification of sweet potato remains and there are no images available except Fig. 4.2, which is of a rather modern specimen. Although most remains in the study by Orliac and colleagues will probably belong to sweet potato, it is important that future studies report the basis on which sweet potato identification was made in archaeological specimens.

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[17] "*On the whole, there are insufficient modern reference studies of these plants to produce solid evaluations of the degree to which tuber anatomy or microfossil characteristics can truly allow an archaeobotanical separation of sweet potato from other related, naturally occurring plants*". (Ladefoged et al. 2005, p. 363).

[18] "*Similarly, starch grains and xylem of sweet potato are not easily differentiated from those of the single indigenous species (*Ipomoea cairica*)*" (Horrocks et al. 2004, p. 153).

5.1 Pollen Grains

In the most comprehensive study of *Ipomoea* pollen morphology to date, Paul Wilkin (1996) reported overlapping pollen grain diameters for *Ipomoea batatas* and for *I. pes-caprae*, 76.7–123.8 μm and 86.4–112.2 μm, respectively. Before Wilkin, Jones and Kobayashi (1969) reported a pollen size in *I. pes-caprae* of 88 ± 2 μm, and Martin et al. (1974a) reported much bigger sweet potato pollen grains (186 μm)—surprisingly big compared to the other studies. More recently, Adi Susanto et al. (2013) reported sweet potato pollen grains very variable in size, 68 to 187 μm, and Srisuwan et al. (2019) measured two sweet potato varieties with pollen sizes 97.9 ± 14.8 μm and 90.9 ± 4.1 μm, respectively. Some of these authors do not explain the method they used to prepare the pollen, but this can dramatically affect the measurement of pollen size. This may be the case in the study by Martin et al. (1974a). However, assuming the results are accurate in the rest of the studies, it is clear that the size of pollen grains in *Ipomoea batatas* and in *I. pes-caprae* overlap.

In terms of morphology, studies show that exine thickness and the overall morphology of the pollen grain are also very similar between species of *Ipomoea* (Jayeola and Oladunjoye 2012; Sengupta 1972; Wilkin 1996), although some authors have attempted to classify the species into different categories based on this (Sengupta 1972; Wilkin 1996). The pollen grains of *I. batatas* and *I. pes-caprae* photographed by Wilkin are in fact very similar in structure and shape, at least in the SEM photographs provided (Plates 3.8 and 3.11, pages 85 and 88, respectively). Both photographs show a pattern of four supratectal processes (spines) per pore, perhaps more regular in *I. batatas*, with processes in both species somehow elongated at the apex. We have not seen optical microscope pictures of *I. pes-caprae* pollen, but photographs of other *Ipomoea* species taken with an optical microscope are also difficult to distinguish from *I. batatas*.

Ipomoea pollen remains have only been reported from Rapa Nui by Horrocks et al. (2012a). These remains are not entire pollen grains but degraded fragments of exine and, although the authors claim *I. batatas* and *I. pes-caprae* pollen can be differentiated, we are sceptical. In the first place, because the finding consists not of entire well-preserved pollen grains but of fragments damaged by acetolysis (see Fig. 7a in Horrocks et al.'s paper). Secondly, our own palynological observations (Wood et al. 2020) show a continuous variation in pollen morphology between species, and the differences do not correlate with phylogeny (see phylogenies in Muñoz-Rodríguez et al. 2019). Broadly speaking, the pollen in *Ipomoea* Clade A (the clade including *Ipomoea batatas*) usually has fewer spines than in other clades, and pollen in clade C (the clade including *I. pes-caprae*) often shows a regular pattern of 4–6 spines around pores, but neither of these patterns is always present (Wood et al. 2020 pp. 48–51). Further, we do not think those structures can be distinguished in the images provided by Horrocks et al. (2012a).

In our experience, pollen morphology is of little use in *Ipomoea* taxonomy. Whereas pollen grains can be identified more or less easily as belonging to the genus *Ipomoea*, it is very difficult, if not impossible, to assign a pollen grain to a specific species or even to a clade with absolute certainty. We remain sceptical about pollen identification at the infrageneric level, and especially if the evidence consists of fragments of pollen grains and not entire grains. Further, the appearance of pollen grains may change depending on whether certain structures remain intact or not after acetolysis (Wood et al. 2020), something that occurred in the study by Horrocks et al. (2012a). In summary, even though the pollen remains found by Horrocks and collaborators may be assigned, more or less confidently, to *Ipomoea*, we do not think it is possible to assign them to a particular species based on their size, and it is certainly very difficult to provide an identification based on their morphology.

5.2 Starch Grains

As far as we are aware, only a few experimental studies of starch granules have been conducted in other *Ipomoea* species besides *Ipomoea batatas*. Apart from a succinct note by Anselme Payen (1826), the first study we are aware of was published in 1854 by Léon Soubeiran. The French chemist studied starch grains from the roots of three Convolvulaceae species: *I. batatas*, *Ipomoea jalapa* (L.) Pursh, and *Operculina turpethum* (L.) Silva Manso.[19] Soubeiran noted the variable size of starch grains in all three of them, as well as the morphological resemblance between the two *Ipomoea* species, also in their central hilum (Soubeiran 1854).

Seventy years later, a meticulous study on starch grains by Edward T. Reichert (1913 pp. 884–885) included *I. batatas*, *I. jalapa* (L.) Pursh, *I. imperati* (Vahl) Griseb.[20] and *I. purga* (Wender.) Hayne, as well as other Convolvulaceae species such as *Calystegia soldanella* (L.) R.Br. and *Convolvulus lineatus* L. Reichert also found that starch grains overlap in size, not only between species of *Ipomoea* but also with other species of Convolvulaceae, and their morphology is similar in different species of *Ipomoea*.

One more study was conducted before the end of the twentieth century and in this case comparing *Ipomoea batatas* and its closest wild relative, *I. trifida* (Kunth) G.Don. Asante et al. (1993) found a bigger average size of starch grains in the cultivated plant, but the size ranges between both species overlap (Table 2 in Asante et al. 1993), thus large grains produced by *I. trifida* plants were bigger than small grains produced by the cultivated *I. batatas*. Asante and collaborators also found that the amylose content was similar or even more extensive in *I. trifida*.

Starch grains are the sweet potato remains most frequently reported from Rapa Nui, yet their identification presents similar challenges to those of pollen grains. Horrocks and Wozniak (2008) acknowledge that *Ipomoea batatas* starch grains are difficult to differentiate from those of *I. pes-caprae*. However, they argue that the starch grains found at Te Niu could belong to *Ipomoea batatas* because *I. pes-*

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[19] Cited as *Ipomoea turpethum* (L.) R.Br., now a synonym.

[20] Cited as *Convolvulus imperati* Vahl, now a synonym.

caprae does not produce storage roots. Although this is true, starch grains can also be found in other plant structures such as stems or leaves (Preiss and Levi 1979), so it is possible that starch grains came from leaves or stems, as well as from non-tuberous roots. Regarding *Ipomoea*, Horrocks (2004) observed that starch grains from *I. cairica* stems are similar to those from *I. batatas* roots. Unfortunately, we are not aware of any study of starch grains in *I. pes-caprae*, which may help identify the remains found by Horrocks and Wozniak in Rapa Nui.

In addition to their similar morphology, starch grain size varies significantly not only between species of *Ipomoea*, but also within species and even within the same plant. Importantly, it is not known how domestication and starch grain formation impact grain shape. In addition, Perry (2002) found that starch grain size and date of deposition do not correlate. Finally, a pilot study using techniques of image analysis found that sweet potato starch grains were often misclassified as other crops by the algorithm—even though no other species of *Ipomoea* or Convolvulaceae were included in the analysis (Wilson et al. 2010). In conclusion, researchers must be cautious in the identification of a sample, or the inference of its cultivated or wild status, based on the size or the morphology of starch grains, as this may lead to erroneous conclusions. Micro-remains may be of some use in identifying certain specimens as belonging to the genus, but assigning the remains to one or another species, based on their size and/or morphology, may prove difficult if not impossible.

In summary, the utility of most archaeological remains to enable differentiation between cultivated sweet potato, non-cultivated sweet potato, and other species of *Ipomoea* is unsatisfactory. External factors such as the geographical location of the deposited remains or their association with human utensils or structures may help assign the remains to sweet potato (see, for example, Horrocks et al. 2012b p. 154). However, researchers taking this approach must be cautious, especially as sweet potato was not the only morning glory species used by humans. Many remains, especially in the Americas but also in the Pacific, will indeed correspond to sweet potato, but other remains may correspond to different morning glory species, and it is currently impossible to assign any remains to any specific species based on biological evidence only. As pointed out by Wilson et al. (2010), the accurate classification of starch grains—and, we would add, of most archaeological remains—, as well as discrimination between domesticated and wild plants, would also require a better understanding of how those processes affect grain shape.

6 Sweet Potato Arrival in Rapa Nui

It is probable that sweet potato was already present in Rapa Nui when Europeans first visited the island. Mentions by Roggeveen and Behrens after the first visit to the island may be open to interpretation, as they do not mention sweet potato explicitly (see footnote 3). However, the crop was already widely cultivated when Felipe González de Ahedo and Cook visited the island. Considering the extent of cultivation reported in the last third of the eighteenth century, together with the various archaeological remains, it seems highly probable (and the rest of this discussion assumes) that the crop was present on the island in pre-European times. In that scenario, we may then ask, when and how did sweet potato arrive on the island? Was the species introduced by Pacific islanders or did it arrive on Rapa Nui by natural means?

Computer-based models published to date do not infer a dispersal of the sweet potato from America to Rapa Nui by natural means. This, on the other hand, does not preclude its dispersal to a different place in the Pacific with subsequent arrival in Rapa Nui. In addition to the molecular phylogenetic analyses and modelling studies mentioned in the introduction, anatomical studies by Guppy (1906) showed that the seeds of some sweet potato varieties have an aerial space that would be compatible with the ability to float. Importantly, a recent study showed that sweet potato seeds are able to germinate after 120 days submerged in sea water, the seed dispersal period estimated from the Americas to Polynesia (Pereira et al. 2020). In addition, long-distance dispersal by natural means is the most plausible explanation for the distribution of over 25 other species of *Ipomoea* in the Pacific, including the Rapa Nui native species *Ipomoea pes-caprae* (Devall and Thien 1989; Miryeganeh et al. 2014; Muñoz-Rodríguez et al. 2018, 2019). It has already been shown that the seeds of *Ipomoea pes-caprae* are able to float and can germinate after 6 months in the ocean so explaining its worldwide distribution (Guppy 1906; Miryeganeh et al. 2014).

If sweet potato dispersed into the Pacific by natural means, it remains unknown where in Polynesia the plant could have landed. We are only aware of one modelling study that explored this question (Montenegro et al. 2008). Montenegro and colleagues show a number of possible landing places for drifting sweet potato seeds, and Rapa Nui is not included among them (see Fig. 4.2 in Montenegro et al.'s paper). However, for reasons not explained by the authors, the model by Montenegro and collaborators only allowed sweet potato floating seeds to depart from coastal Ecuador, whereas the estimated natural distribution of the species in the Americas is much broader (Wood et al. 2020). The restricted departure points of sweet potato seeds from coastal America in that study resulted in no expected contacts with Rapa Nui, but a broader departure region could provide quite different results. In addition, we are not aware of any study that modelled the possibility of an arrival in Rapa Nui by natural dispersal from other Polynesian islands, which would also be interesting. Future studies may provide further evidence of where in the Pacific sweet potato could have arrived in a scenario of long-distance dispersal by natural means, or, alternatively, reject the possibility of its arrival in Rapa Nui by natural means.

The alternative to long-distance dispersal is that sweet potato was transported onto Rapa Nui by humans. People could have arrived from elsewhere in Polynesia or directly from the American continent, as postulated by several authors (Heyerdahl 1952; Heyerdahl and Ferdon Jr. 1961, p. 522). Despite the passionate defence of the latter possibility by Heyerdahl and other authors, all alleged evidence supporting a transfer of the crop from the American continent to Polynesia and Rapa Nui is weak at best (Muñoz-Rodríguez 2019). It seems indisputable, not only from oral traditions but also from other lines of evidence, that contacts between inhabitants from different Pacific islands in ancient times existed (Best 1925; Buck 1938; Cox and Banack 1991; Hornell 1946). Therefore, if the sweet potato was present anywhere else in the Pacific in ancient times (regardless of whether it got there by human transport or natural means), Polynesians could be responsible for its dispersal throughout the region and its introduction to Rapa Nui.

To date, all archaeological remains from Rapa Nui assigned to sweet potato have been dated to 625–513 cal BP (c. 1300–1400 AD; Horrocks et al. 2012b) or more recent times. *Ipomoea* remains have not been reported in studies from earlier dates. However, studies only report pollen grains, and only one pollen remain has been reported from the island (Horrocks et al. 2012a). The lack of *Ipomoea* pollen remains may be due simply to its absence from the area or perhaps to animal pollination of *Ipomoea* species. Further, many studies were focused on the Rano Raraku, Rano Aroi, and Rano Kao craters areas, where no sweet potato remains, apart from those reported by Horrocks et al. (2012a) have been found.

It is now thought that only coastal areas of Rapa Nui were cultivated during the first centuries of human presence on the island, whereas inland territories including the three volcanoes would have remained forested for a longer time (Horrocks et al. 2017; Ladefoged et al. 2013). This may also explain the lack of sweet potato archaeological remains from all except Rano Raraku (if it truly is sweet potato but see previous section). Further, the presence of yams but not sweet potato in the pre-1300 sample studied by Horrocks and Wozniak (2008) is compatible, as hypothesised by the authors, with the proposal that sweet potato cultivation started at around 1200–1300 AD, and therefore later than yam cultivation, as postulated in other studies based on changes in the agricultural system (Wallin et al. 2005).

In summary, the limited evidence currently available is most compatible with a human-mediated introduction of sweet potato to Rapa Nui at around 1300 AD, possibly not by the first colonisers but in a later arrival (Wallin et al. 2005). This possibility, of course, assumes that remains identified as sweet potato truly are of sweet potato and did not originate from other species. Data currently available, including indirect evidence, is compatible with the remains being sweet potato, but we cannot dismiss the possibility that at least some of them were other species. On the other hand, the absence of *Ipomoea* remains in the oldest soil samples available, mostly from non-coastal locations, does not exclude the presence of *Ipomoea batatas*, *I. pes-caprae* or other species of Convolvulaceae nearer the coast in more ancient times, either as a result of long-distance dispersal or human introduction. Even in the case of a human-mediated introduction, it could have occurred pre-1300 AD. Future analyses that demonstrate the existence (or the lack of) sweet potato remains in coastal locations in ancient times may further inform the question of how sweet potato arrived on Rapa Nui.

Acknowledgements We thank Catherine Orliac for sharing with us several important documents that we had been unable to find, as well as for providing the photograph of a sweet potato storage root in Fig. 4.2. Thanks are also due to Stephen Harris, Corinna Hartinger, and Benedikt Kuhnhaeuser for their help with the translation of several historic texts.

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Chapter 5

Pre-European Contact Sweet Potato (*Ipomoea batatas*) at Rapa Nui: Macrobotanical Evidence from Recent Excavations in Rano Raraku Quarry, Rapa Nui

Jo Anne Van Tilburg, Jennifer M. Huebert, Sarah C. Sherwood, and Casey R. Barrier

1 Introduction

The geographical remoteness and physical location of Rapa Nui relative to coastal South America have long encouraged research speculation about the island's possible role, if any, in the transfer into Polynesia and subsequent dispersal of sweet potato (*Ipomoea batatas*; *kumara*) (Dixon 1932; Stokes 1932; Heyerdahl and Ferdon Jr. 1961; Yen 1974; Green 1988, 2001, 2005; Clarke 2009; Scaglion and Cordero 2011).[1] New evidence is presented in this chapter for the first well-documented, directly dated, pre-European contact find of carbonized sweet potato

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[1] Phonetic annotation of RAP *kumara* and New Zealand (Aotearoa) MAO *kūmara* (kuumala) are distinguished as needed here according to Pollex.

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_5

tuber, which was derived from recent excavations in Rano Raraku, the monolithic statue (*moai*) quarry (Horrocks 2014; Sherwood et al. 2019).

Carbonized sweet potato tubers are uncommon in Polynesian archaeological sites and rare for Rapa Nui, and the material we report joins the small number of reported macro-botanical finds in the region (e.g., Ladefoged et al. 2005a; Rosendahl and Yen 1971; Kirch 2017a). Synthesis and evaluation of the currently available archaeological evidence for sweet potato in eastern and southern Polynesia provide the most recent regional context (Anderson and Petchey 2020) within which the limited body of previously published evidence for Rapa Nui is described. The integration of the new find and its described context into that record lends considerable insight into the human use of Rano Raraku statue quarry. It contributes to the existing record of pre-contact *Ipomoea batatas* in East Polynesia, facilitates more direct comparisons with finds from other regional locations, and assists in constructing more targeted models of Rapa Nui origins and post-settlement contacts.

2 Synopsis: Evidence of Rapa Nui *kumara*

2.1 Previous Archaeological Evidence

Fragments of charred tubers were first reported for Rapa Nui in association with an excavated earth oven (*umu*) inside a double-walled circular structure used as a "dwelling" at ʻAnakena (Site E-2; Skjølsvold 1961:295). As Skjølsvold (1961:295) clearly stated such structures had multiple types of reuse including gardens or temporary habitations, thus casting doubt on sample provenance. Skjølsvold (1961) achieved a radiocarbon date (K-522) of 430 ± 100 BP (reported by Smith 1961) on unidentified wood charcoal collected in the *umu* (Mulrooney 2012:848; cal 1σ 1437–1619). The E-2 date is here recalibrated using the 2020 atmospheric curve to cal AD 1324–1799 (95.4% probability) or cal AD 1390–1674 (91.1% probability). We were unable to locate for further study any archived, remnant material or a lab report documenting these data.

Orliac (1998, 2000) and Orliac and Orliac (1996, 1998a, b) described three sites they tested in 1995. The first is a modest dwelling (singular) also described as houses (plural), along with cooking areas inside these habitations. The second is a pit at Orongo, and the third is the mapped cluster of habitations at Akahaŋa (Cristino Ferrando et al. 1981). Vargas Casanova et al. (2006:269, 272, Table 6.10) provide two radiocarbon determinations each for Akahaŋa sites 7-571a and 7-551 (citing Orliac 2000:211–218) but correctly point out that the entire complex of habitation sites at Akahaŋa was often used and reused post-European contact. The three sites yielded at least 200 samples of food plants including *kumara* fragments identified using a standard light microscope (Orliac and Orliac 1996; Pearthree 1996; Vargas Casanova 1998). Mulrooney (2012:823–825) notes that identified wood charcoal used in dating these sites was fuel waste but that the dating method employed was unknown and may have been a bulk date. Orliac and Orliac (1998a, b) concede uncertainties in the dates they received and suggest a relative chronology (old, intermediate, and recent) for the sixteenth to nineteenth centuries. Robinson and Stevenson (2017) critique the dates on the Orliac samples and note that they are stratigraphically inconsistent. Wallin et al. (2005) describe persistent issues relative to *umu* stratigraphy. A single radiocarbon date is rarely capable of representing the entire occupational span in Rapa Nui habitations of all types and not particularly dependable (Mulrooney et al. 2021), and dates from *umu* may not relate to the actual burning event that produced the charred material. This brief overview of *kumara* evidence points to site type challenges and the apparent need for more critically evaluated, informed radiocarbon date context reporting in Rapa Nui archaeology.

Finally, analysis of starch traces is an important tool in sweet potato research (Allen and Ussher 2013). Starch grains are reported in soils from agricultural pit features at Te Niu on the west side of the island and found in contexts possibly as early as the late thirteenth century AD (Horrocks and Wozniak 2008; Wozniak 1999, 2001). *Ipomoea* pollen grains, and possibly starch grains, are reported in pre-contact contexts in one sediment core from the Rano Raraku lake (Horrocks et al. 2012). It is worth noting that the Rano Raraku profile sediment samples collected during the excavations discussed here (Sherwood et al. 2019) did not reveal certain evidence of any starch remains, although it is possible that reflects a taphonomic issue.

2.2 Ethnohistorical Observations

Five calls at Rapa Nui by fleets from five different group arrived during the first century of contact: Dutch (1722), Spanish (1770), English (1774), French (1786), and American (1795). The Dutch fleet was led by Jacob Roggeveen (Corney 1908). The first anchorage site is unknown, but it was on the north coast somewhere between ‘Anakena and Ahu Heki‘i. How far inland the landing party ventured is unknown. The island was said by Sergeant-Major Karl Friedrich Behrens, who sailed with Roggeveen (Corney 1908:135), to be productive and he noted bananas and potatoes under cultivation. Roggeveen (Corney 1908:13) noted “root crops.” Don Francisco Antonio de Agüera y Infanzon (Corney 1908:97), Chief Pilot of the Spanish expedition (1770) also described “roots” offered with other foods.

After an altercation in which at least a dozen Rapa Nui people were killed or wounded the Dutch were offered “many roots, some red, some white, a good lot of potatoes which tasted almost like bread...” The word “roots” did not always or specifically refer to sweet potatoes but could have referenced yams as well (Corney 1908:13, n. 1). Behrens (Corney 1908:135) further noted that “the fields or lands were all measured off with a cord, and very neatly cultivated.” Captain James Cook judged potatoes [presumably *kumara*] to be “the best of the sort I ever tasted” (Price 1971:155). Engineers and artists who sailed with the French expedition led by Jean-François de Galaup de la Pérouse produced a valuable illustrated map of bounded agricultural fields inland along a length of the island's west coast (Dunmore 1994; McCoy 1976).

Roggeveen (Corney 1908:19) identified a "King or Head Chief" who through gestures invited the Dutch to "go to the other side of the Island" where they would find the "principal place of their plantations and fruit-trees, for all the things they brought to us of that kind were fetched from that quarter [part]." That "principal place" would be the southeast region of Hotu 'Iti, the location of Rano Raraku and one of two ethnographically known lineage-based sociopolitical regions (with the west being Ko Tu'u) (Routledge 1919:221–223, Fig. 91). Overall, the sweet potato (grown in demarked fields) and banana (grown in clustered gardens) dominated the limited range of foods presented by the Rapa Nui to these first visitors, with chicken, both alive and cooked, proffered often and in quantity.

Métraux (1940:153–4) summarized ethnographic accounts attesting to the importance of the "eternal sweet potato" as "the everyday dish" in the traditional diet of Rapa Nui (Tromp and Dudgeon 2015). He recorded 25 Rapanui names for sweet potato, all formed by adding adjectives describing such traits as tuber color or shape. Included are two names for those that are slightly red and at least 12 for those that are various shades of white (Métraux 1940:154). The naming protocol suggests the plant's variety, antiquity, and value as a Rapa Nui food source (Métraux 1940:154). Barthel (1978) states that taro was a high-status food while sweet potato was not. Despite these early ethnohistorical observations of widespread cultivation and the unarguable presence of sweet potato, no archaeological evidence for sweet potato in large-scale dryfield contexts has been found to date (Vargas Casanova et al. 2006; Stevenson and Haoa Cardinali 2008).

3 Rano [a] Raraku: The Statue Quarry

3.1 Physiography and Sculpture

Rano [a] Raraku (E: 669564.258; N: 6,998,616.107) is a semicircular erosional geomorphic feature having a 2.9-km base circumference at the 50-m contour level and with an elevated rim measuring ~800–900 m across (Fig. 5.1). Elevation is ~100 m ASL in the west and north and ~160 m ASL in the south and east. Rano Raraku is contained within a discretely mapped archaeological zone or sub-quadrangle of relatively flat land (Cristino Ferrando et al. 1981) that, when the surface area is rendered in 3D comprises 1.39 km^2. The Easter Island Statue Project (EISP; www.eisp.org) has compiled data records for 917 megalithic stone sculptural objects (MSSO) within the sub-quadrangle, of which 661 are within the 50 m contour base level of 0.605 km^2. The unique morphology of Rano Raraku gives it a significant geographical presence on the Rapa Nui landscape (Fig. 5.2) (Routledge 1919; Métraux 1940; Englert 1978; Dunn et al. 2013, 2015).

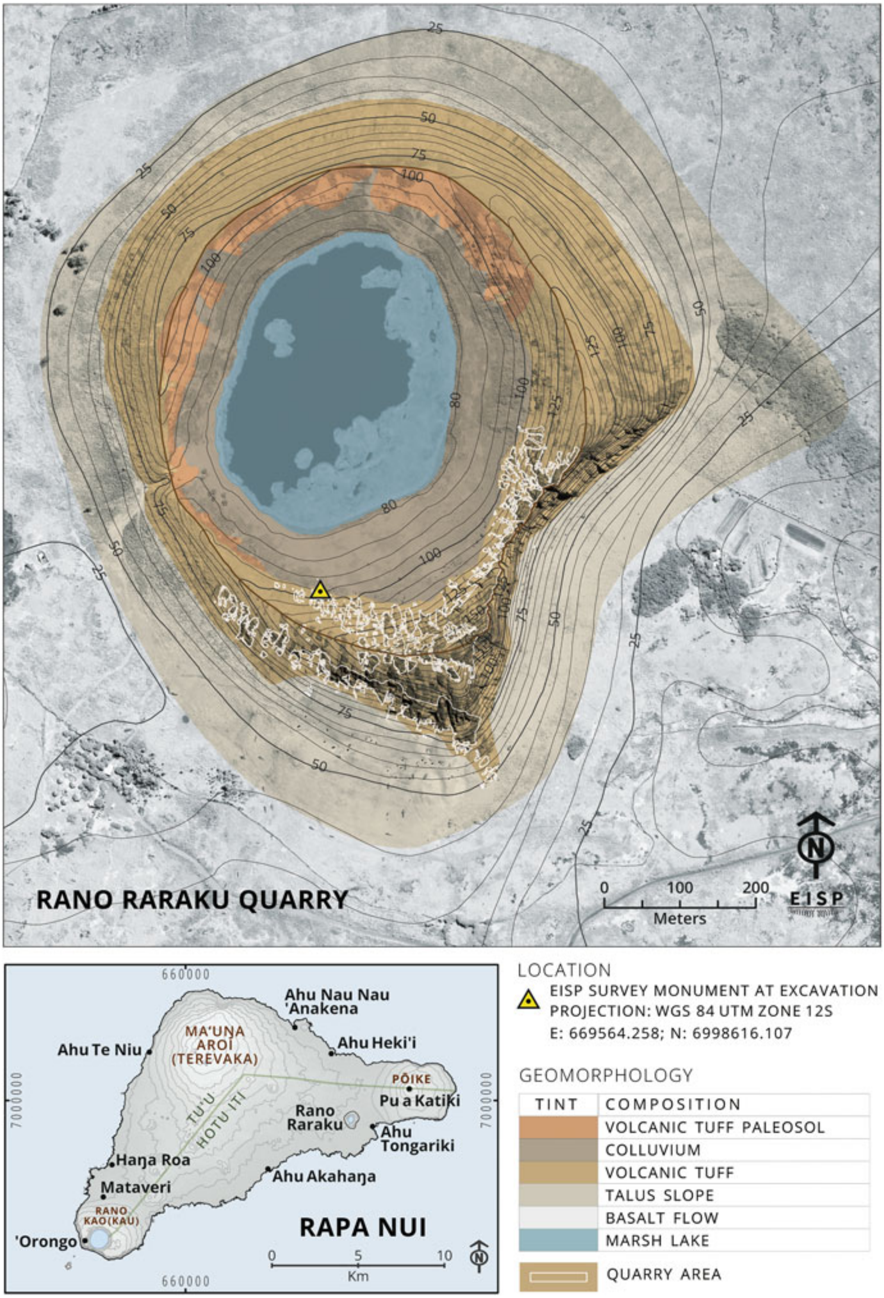

Fig. 5.1 Topographic and archaeological survey map, Rano Raraku (contour interval, 5 m), with quarried objects outlined and geomorphology indicated, 2021. Map, EISP; base map, Instituto Geográfico Militar de Chile, 2004; satellite image © Digital Globe, Inc.; geomorphic overlays, Dunn et al. (2013, 2015); cartographic illustration, A. Hom (adapted, Sherwood et al. 2019)

Fig. 5.2 Rano Raraku Exterior Region slopes, quarries, and statues. Photograph, EISP

Addressed the rainfed lake (*rano*) at the core of Rano Raraku has been the focus of multiple palynological studies producing reports that often conflict (e.g., Skottsberg 1921; Flenley 1979, 1994, 1996, 1998; Flenley and King 1984; Dransfield et al. 1984; Flenley et al. 1991; Flenley and Butler 2018; Sáez et al. 2009; Cañellas-Boltà et al. 2013). The lake edge is ringed with dense stands of reeds (*Schoenoplectus californicus;* totora) forming floating mats that move with the winds and leave root tracks across the lake bottom (Wachsmann and Morris 2012). As Yen (1988:66) pointed out, the totora reed was a domesticate seen growing in household gardens by the Spanish expedition of 1770. This suggests that a natural asset present in the interiors of both Rano Raraku and Rano Kao (Kau) was adapted to provide significant economic opportunities (Horrocks et al. 2012; Sherwood et al. 2019). The depths of the Rano Raraku lake naturally fluctuate over time, and it is ethnographically reported that the lake was a swamp in the mid-1800s (Routledge 1919). Lake depth in 2012 was measured at 2.9–3 m (Wachsmann and Morris 2012). The totora phytoliths in our dryland samples from Quarry 2 suggest selective application of lake water, vegetation, or organic sediments with the probable objective of augmenting soil fertility (Sherwood et al. 2019:17).

3.2 Rock, Soils, and Fertility

The bedrock of Rano Raraku is made up of an palagonite tuff of phreatomagmatic origin (Baker et al. 1974; Baker 1967, 1974, 1993; Charola and Lazzarini 1998; Charola 1997; De Witte et al. 1994; Domalowski 1981; Friese et al. 2005; Gioncada et al. 2010; Gonzalez-Ferrán and Baker 1974; Lazzarini et al. 1996; Margottini and Pandolfi 2008; Margottini et al. 2013; Moreno Roa 1994; Van Tilburg 1993; Van Tilburg et al. 2008). The material is suitable for carving but difficult to date and nearly impossible to protect from weathering when exposed in its natural state (Bahamondez Prieto 1994; Bahamondez Prieto and Valenzuela 2004; Margottini and Pandolfi 2008; Van Tilburg et al. 2016).

The geomorphology of the Rano Raraku Interior Region includes soils mapped as volcanic tuff paleosol and colluvium (Dunn et al. 2013, 2015; Van Tilburg et al. 2019a). The 21 upright *moai* in Rano Raraku Interior Region stand at the interface of these two weathering boundaries. The soils encountered in the Quarry 2 excavations are generally dark yellowish-brown (10YR 4/4) silt loam to clay loam with limited soil structure and a course fraction composed of variable concentrations of unsorted weathered gravel-size rock fragments that include tuff and a few subangular fragments of basalt from the tuff. The stratagraphic boundaries between the zones (below 1 m there is no horizonation) are generally clear and smooth suggesting that these deposits represent pulses of parent material generated through both anthropogenic processes (e.g., quarrying) and natural processes (e.g., slope wash) moving downslope with periods of intermittent stability.

The analysis reported in Sherwood et al. (2019) demonstrated that despite the general characterization of the island’s soils as depleted (Stevenson and Haoa 1998; Wozniak 1999; Stevenson et al. 2002; Ladefoged et al. 2005b, 2013; Louwagie et al. 2006; Louwagie and Langohr 2002), the Rano Raraku Interior Region soils have relatively high levels of extractable P and Ca, which are ideal for agriculture. Perhaps most important is the fact that these soils data, which are derived from the process of quarrying tuff, are relatively consistent throughout the profile. This finding indicates that the Rano Raraku soils have potential to produce high agricultural yields.

4 Modern Site Environment Context

The Rano Raraku Quarry 2 excavation site is situated in the westernmost area of the established Interior Region quarries (Fig. 5.3). A weather station was established on the site in 2010 (94 m ASL; Fig. 5.4a, b) and data were processed as monthly averages for comparison, as usual, with Mataveri airport meteorological data (69 m ASL) (Fischer and Bahamondez Prieto 2012). Preliminary analyses showed a major difference in wind directions and velocities (Fig. 5.4c) but otherwise good correlations between Mataveri and Quarry 2 for rainfall (Fig. 5.4d), air temperature

Fig. 5.3 Rano Raraku Interior Region quarries, slopes, and lake, EISP excavation site indicated. Photograph, EISP

(Fig. 5.4e), and relative humidity (Fig. 5.4f). Differences in local environmental conditions or agricultural potential may be attributed to altitude and the unique physiography and geomorphology of Rano Raraku (Junk & Claussen 2011).

4.1 Previous Mapping and Excavations

The first known Western presence in Rano Raraku Interior Region was in 1868, nearly 150 years after first contact in 1722. Preliminary mapping of Rano Raraku as a discrete zone or sub-quadrangle was carried out by the Mana Expedition to Easter Island, 1914–1915 (Routledge 1919). Encouraged partly by wide-spread publicity following that early work at least 60–70 sub-surface intrusions of various statues in Rano Raraku occurred without oversight or reporting until about 1960. Modern excavations (Heyerdahl and Ferdon Jr. 1961), mapping (Cristino Ferrando and Vargas Casanova 1980; Cristino Ferrando et al. 1981), and multiple surface surveys have been carried out in Rano Raraku since the mid-1970s (Englert 1978; Cristino Ferrando and Vargas Casanova 1980; Cristino Ferrando et al. 1981; González Nualart et al. 1988; Van Tilburg and Casanova 1998; Vargas Casanova et al. 2006). In 2002, Easter Island Statue Project teams initiated modern GPS mapping of the entire Interior Region with a particular focus on the previously unmapped but outlined quarries. In 2009, Phase 1 of the project's Excavation and Conservation Initiative for Rano Raraku Interior Region began under a comprehensive permit granted for Rano Raraku by the Consejo de Monumentos Nacionales (CMN).

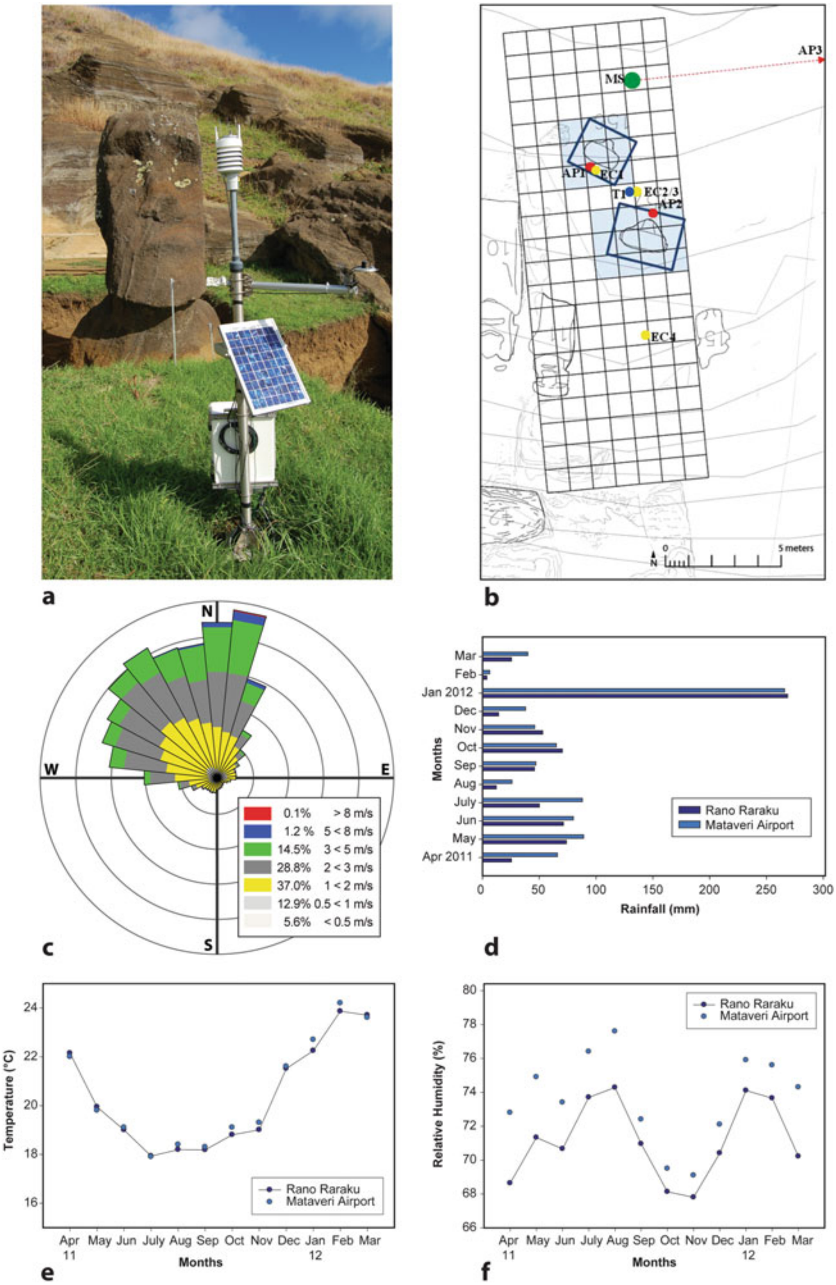

Fig. 5.4 (**a–f**) Weather station (**a**) installation, Rano Raraku, Quarry 2, *moai* 157; (**b**) plan of sensors buried 20–50 cm; (**c**) wind directions and speeds; (**d**) monthly rainfall totals; (**e**) average monthly air temperature; (**f**) average monthly humidity; all values, April 2011–March 2012. Photograph, EISP; illustrations, Fischer and Bahamondez Prieto (2012)

4.2 Stratigraphy and Sampling

Quarry 2 and the surface of the surrounding slope were cleared of the brush during the pre-excavation phase (Fig. 5.5a) and 1–2 m of slope deposits within the main quarry chamber were removed and screened, thus revealing previously obscured quarrying evidence, rock art embellishment on the walls and suites of petroglyphs on both *moai* 156 and 157 (Van Tilburg et al. 2019a and Van Tilburg 2021). This early excavation phase (Fig. 5.5b) allowed further mapping definition of the main quarry chamber known ethnographically as Papa Haa Puré as well as intensive analysis of rock art on the dorsal sides of both statues (Routledge 1919, Figs. 70, 71; Van Tilburg et al. 2019b; Fig. 5.5c) and throughout Rano Raraku Interior Region. The main quarry chamber was overlain with a grid of 1 m squares. As sediments were removed, they were passed through wire mesh screens (3.1 mm). Lithostratigraphic units (zones) were designated during the excavation when possible and later in the profile and described by Munsell color, texture (including clasts > coarse sand), structure, other pedogenic features, and the nature of contacts (Sherwood et al. 2019). Five profiles were documented for vertical excavation exposures (Sherwood et al. 2019: Fig. 5.6, 5.7).

Fig. 5.5 (**a–c**) Statue 156 Quarry 2, Rano Raraku (**a**) pre-excavation, 2006; (**b**) excavation, 2011; (**c**) dorsal view, 156 with petroglyphs. Photographs, EISP

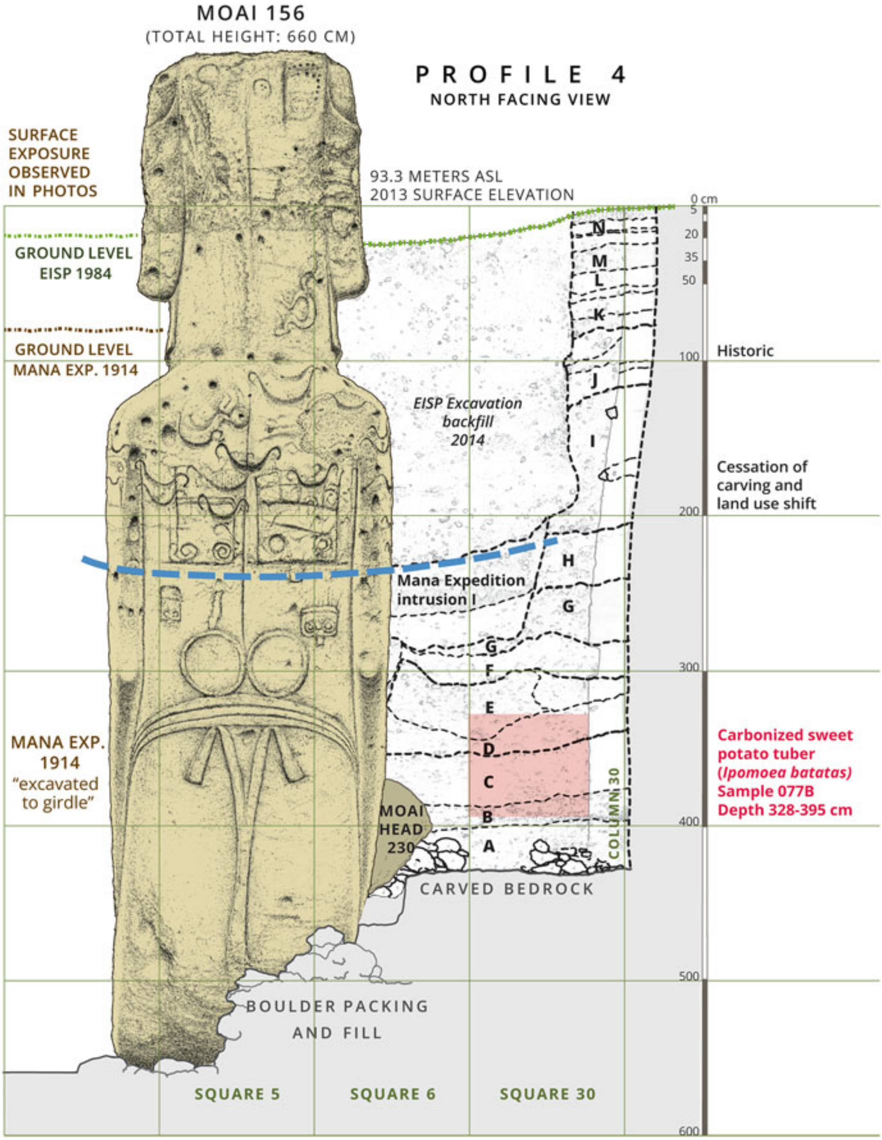

Fig. 5.6 Statue 156, Profile 4, with blue dashed line estimating temporary surface stability and petroglyphs applied (modeled Phase Zone H; adapted, Sherwood et al. 2019). Provenience of carbonized *Ipomoea batatas* tuber (156-30-B/C). EISP; illustration, A. Hom; drawing, C. Arévalo Pakarati

Three types of samples were collected from Profile 5 including bulk sediment samples (ca. 150 g) (for microbotanicals and soil chemistry), soil/sediment intact micromorphology blocks, and a continuous vertical float column from Square 30

Fig. 5.7 Column excavation, Rano Raraku Interior Region, Quarry 2, *moai* 156, Square 30. Photograph, S. Sherwood

(for additional control of microbotanicals and radiocarbon samples). The float column inserted in the main excavation block of 156 measured 20 × 40 cm and extended to 430 cm below surface to exposed rock packing. Samples were collected by zones and floated using hand agitation in a large water basin and recovered as light and heavy fractions. The light fraction was targeted for radiocarbon samples having well-defined contexts.

4.3 Identification of Ipomoea batatas

A total of 37 screen samples collected from the excavation of *moai* 156 were analyzed; two screen samples from *moai* 157 and nine light fraction float samples from the column. Freshly fractured transverse and tangential facets of charcoal fragments were examined with an epi-illuminated microscope at magnifications of 50–500×. Taxonomic identifications were made by comparing anatomical characteristics with Pacific Island woods in vouchered collections.

Several fragments of parenchyma were encountered in a charcoal sample collected from *moai* 156, Square 30, Zone B/C at 328–395 cm below ground

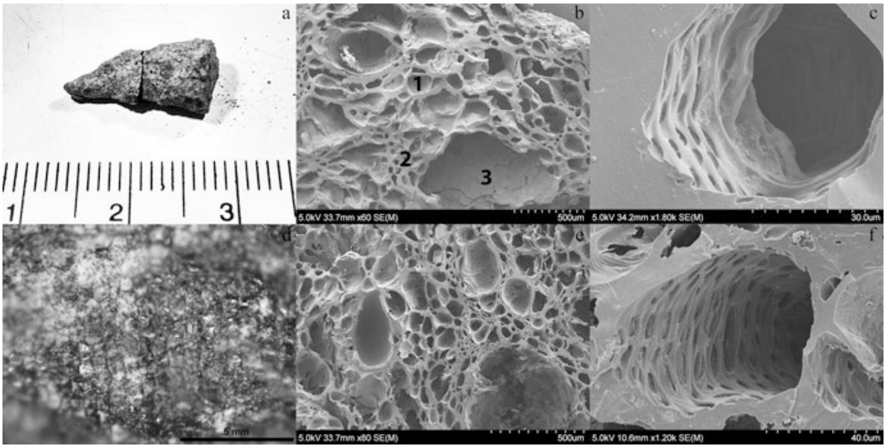

Fig. 5.8 (**a–f**) Sweet potato tuber fragments: (**a**) specimen Unit 156, Square 30, sample 077B; (**b**) SEM images of fragment showing large parenchyma cells [1], cambial cells [2], and large fractures [3]; (**c**) close-up of vessel wall; (**d**) close-up of exterior surface; (**e, f**) charred reference specimen of fresh *Ipomoea batatas* showing comparative anatomical features. Photographs, J. M. Huebert

surface (Fig. 5.8a–f). One is a hard, fissured fragment of the tapered end of a tuber that superficially retains the thin-walled cellular structure of periderm. A second fragment with similar cell structures, but having indistinct morphology, was also identified. These materials were examined with a Scanning Electron Microscope (SEM) and each displayed vascular tissue consistent with sweet potato (*Ipomoea batatas*; Fig. 5.9). Such features include large storage parenchyma cells and vascular tissues that have xylem elements and associated cambia. These structures are unlike the tuberous roots of yam (*Dioscorea* sp.), taro corms (*Alocasia* sp. and others), the rhizomes of *ti* (*Cordyline fruticosa*), or tap roots such as that of *Ipomoea pes-caprae* (beach morning glory, once common on the Ahu Tongariki site). Large and small fissures are also noted, suggesting that the materials contained some moisture when charred since tension fractures occur in sweet potato tubers when they are burned fresh (Ussher 2015:311).

4.4 Radiocarbon Results

A portion of the tapered *Ipomoea batatas* fragment was removed for dating. It returned a conventional radiocarbon age of 350 ± 30 BP (Beta 447,618; δ 13 C = −21.2), or cal AD 1487–1648 (95% probability) (Fig. 5.10a, b).

To put this tuber fragment find within a wider temporal context a Bayesian model of the excavation of *moai* 156 was developed, based on 20 radiocarbon dates (Sherwood et al. 2019: Fig. 12) (Fig. 5.11). Dates were all obtained from charred, short-lived materials including paper mulberry (*Broussonetia papyrifera*) twigs and

Fig. 5.9 Modern sweet potato tubers cultivated in a private Rapa Nui agricultural field. Photograph, S. Haoa Cardinali

the tuber fragment itself. The calibrated and modeled (italicized) dates presented below were updated with OxCal v4.4.2 and the recent SHCal20 atmospheric curve for the Southern Hemisphere (Bronk Ramsey 2009; Hogg et al. 2020). Inspection of the results shows that the two versions of the model do not significantly differ, with modeled date-range endpoints (rounded to 5 years) shifting only 5–10 years in some cases. Overall, the beginning of agricultural activities in this area of Rano Raraku Interior Region is therefore estimated to have occurred by *cal AD 1450–1600 (95% probability)*, with an endpoint probably reached by *cal AD 1665–1760 (95.4% probability*). Within the context of the model, the *Ipomoea batatas* fragment itself is placed at *cal AD 1510–1650 (95% probability)*. Thus, the direct date and the modeled date place the tuber in Rano Raraku well before first reported European contact (1722).

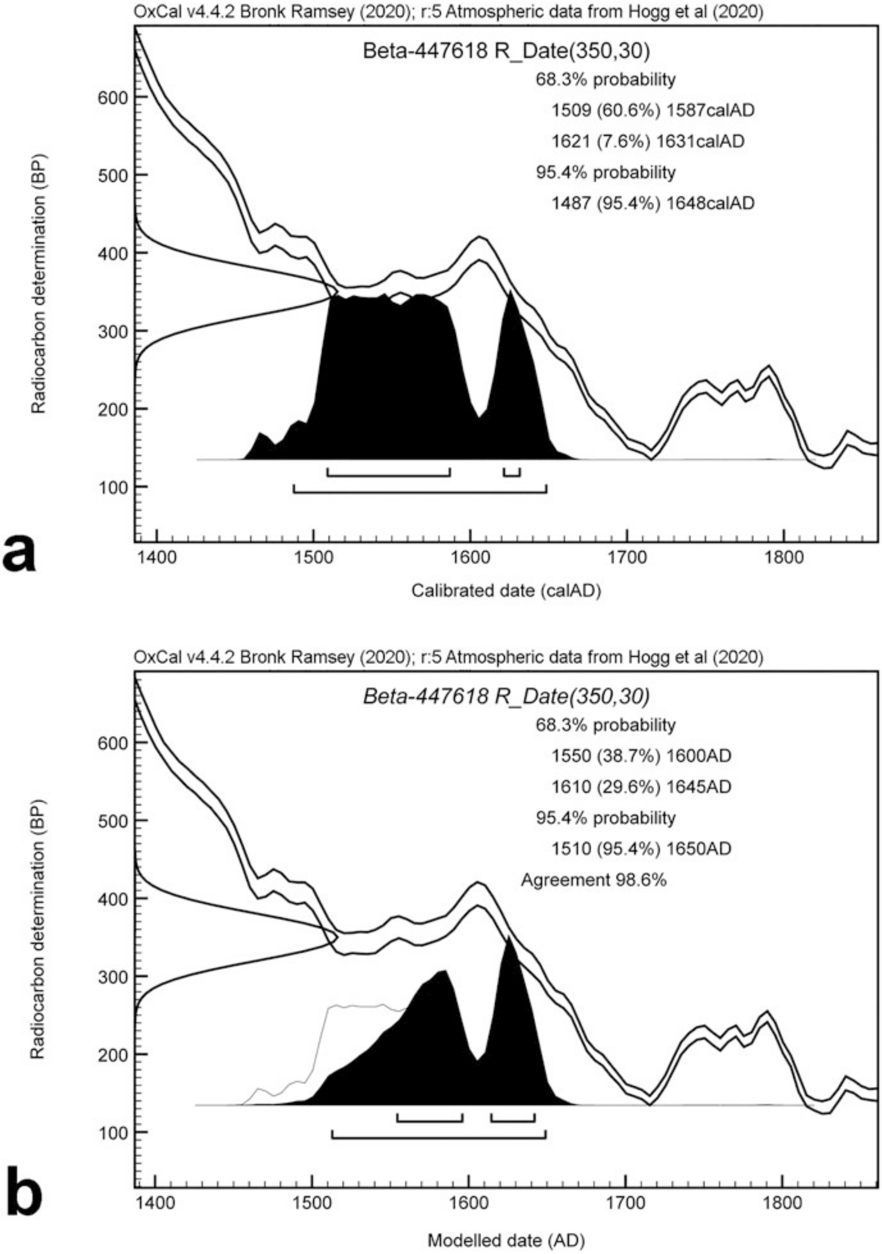

Fig. 5.10 **(a, b)** Radiocarbon dates, Quarry 2, statue 156 *Ipomoea batatas* (**a**) calibrated and (**b**) modeled (Sherwood et al. 2019)

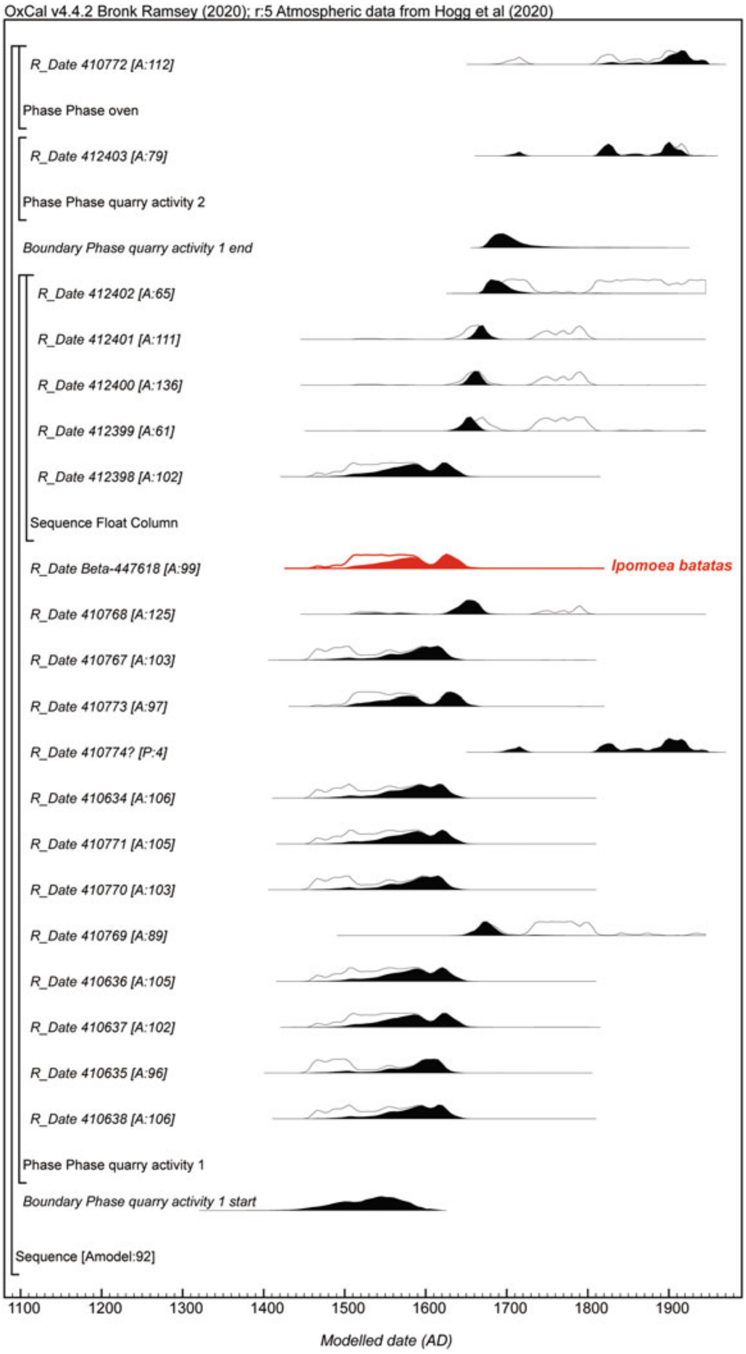

Fig. 5.11 Radiocarbon calibration and Bayesian Multiplot Model based on analysis of twenty 14C ages (adapted, Sherwood et al. 2019: Fig. 12) and updated to Oxcal v4.4.2 (Bronk Ramsey 2020); r:5 atmospheric data, Hogg et al. (2020)

4.5 Curation

A secondary portion of the tuber sample identified as *Ipomoea batatas* was retained prior to being sent for dating to facilitate future studies. Other materials logged, measured, photographed, and bagged and labeled by square, level, and material type are curated at the Museo Antropológico Padre Sebastián Englert, Hanga Roa, Rapa Nui. The excavation was documented over phases and seasons from 2009 to 2015 using multiple means including standard photography, drone photography and video, and photogrammetry and generated various preliminary interagency reports and selected publications (copies of all reports are on file, Easter Island Statue Project Archive and Database).

5 Rapa Nui and the Regional Context

Anderson and Petchey (2020) surveyed the available archaeological evidence for sweet potato within Polynesia and particularly for New Zealand (Aotearoa). In focus were fragments of carbonized tuber found in the Tangatatau rockshelter (MAN-44), Mangaia, Southern Cook Islands (Kirch 2017b). A sample identified there as *Ipomoea batatas* was originally suggested to date to ca. AD 1000 (Hather and Kirch 1991). Recent re-dating of the context has produced a range of cal AD 1461–1627 (95.4% probability) (Kirch 2017b: Table 5.3), which is interpreted as supportive of sweet potato transfer into central Polynesia no later than the end of the fourteenth century AD (Kirch 2017a:208–210, 2017b).

The evidence provided here for a direct date of cal AD 1487–1648 (95% probability) on one *Ipomoea batatas* sample from the Rano Raraku excavations may be considered in light of that interpretation. Moreover, the Rano Raraku evidence addresses the need for more accurate dating of recovered sweet potato materials and their contexts as advocated by Anderson and Petchy (2020:353). While some recent attempts at chronological evaluations for Rapa Nui have been contentious (Hunt and Lipo 2006; Wilmshurst et al. 2011; Mulrooney 2012, 2013; Lipo and Hunt 2016) others have focused on the targeted redating of site types (Mulrooney et al. 2021). The find reported here is pertinent to agricultural models for Rapa Nui (Stevenson et al. 2015; Puleston et al. 2017) but also to future chronological analyses or model building within the larger region (Weisler 1993, 1994, 1996, 1998; Weisler and Green 2011; Weisler et al. 2016).

6 Conclusions

To reiterate, direct evidence presented here has established the pre-European contact presence of *Ipomoea batatas* (*kumara*; sweet potato) on Rapa Nui. This information is key to further investigation of Rapa Nui settlement scenarios, post-settlement contact options, and subsistence practices, especially as they are related to resource concentration and soils fertility in Rano Raraku. Specifically, one *Ipomoea batatas* fragment is dated in the context of a Bayesian model at *cal AD 1510–1650 (95% probability)*. In the same context, we set the beginning of agricultural activities in Rano Raraku Interior Region to *cal AD 1450–1600 (95% probability)*, with the cessation of activities *cal AD 1665–1760 (95.4% probability)*.

A range of native and introduced cultivated plants (Sherwood et al. 2019) on Rano Raraku Interior Region slope is attested by the combined macro and microfossil data contextualizing the reported *kumara* find. In looking ahead, and to frame this study further, it is apparent that highly standardized direct dating, consideration of taphonomy, and standard calibration practices are required for new model building and testing in Rapa Nui archaeology. Integration of this rare, contextualized find into the existing East Polynesian record of pre-contact Ipomoea batatas facilitates direct comparisons within the region and assists in the constrution of targeted models of Rapa Nui origins and post-settlement contacts.

Acknowledgments J.VT. thanks the Archaeological Institute of America Site Preservation Committee; the Consejo de Monumentos Nacionales, Secretaria Técnica de Patrimonio Rapa Nui; Alberto Hotus Chavez and the Conosejo de Ancianos Rapa Nui; Ninoska Cuadros Hucke and the Parque Nacional Rapa Nui, the Rano Raraku excavation team members and Cristián Arévalo Pakarati, Alice Hom, Sonia Haoa Cardinali, and Lilian González Nualart, as well as Gail Murakami of International Archaeological Research Institute, Inc. (IARII), who analyzed additional macrobotanical samples from this site. J.H. thanks Ella Ussher (Australian National University, Canberra) for advice regarding parenchyma identification, and the staff at the Biological Electron Microscope Facility, University of Hawaii-Mānoa, for assistance with the SEM. All authors extend appreciation to the editors of this volume for their invitation to participate.

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Chapter 6
Anakena Re-visited: New Perspectives on Old Problems at Anakena, Rapa Nui

Paul Wallin and Helene Martinsson-Wallin

1 Introduction to the Problem

It is now over 30 years since we participated in the large-scale archaeological excavations at Anakena (Fig. 6.1). The results of the excavations are published in the Kon-Tiki Museum Occasional Papers (Skjølsvold 1994).

The accumulated results from archaeological research on Rapa Nui subsequent to our initial excavations at Anakena justify a re-assessment of the remains and the chronological aspects at this site. New radiocarbon-dated samples have been added to the analysis and discussion of Rapa Nui prehistory, and old samples have been re-analyzed several times (see, for example Martinsson-Wallin et al. 2013; Martinsson-Wallin and Crockford 2002; Wallin et al. 2010; Wilmshurst et al. 2011).

In this respect, we suggest that it is important to re-analyze the activity and settlement sites and monuments at Anakena and their importance for ritual activities from the time of initial colonization onward. The aim of this paper is to provide new explanations and interpretations of the formation processes of the Anakena site with special attention to the activity area we named Nau Nau East (Fig. 6.2). Features observed in this activity area included a small standing stone image upright that was crudely carved, hearths, refusal pits, postholes, grinding activities and a stone line demarcation.

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_6

Fig. 6.1 Overview with site locations at Anakena. Photo: Paul Wallin

Fig. 6.2 Excavation of the site Nau Nau East in 1988. The crude image upright is visible in the rear trench. Photo: Paul Wallin

1.1 Chronology

At the time of our excavations in the Anakena area in the late 1980s, Arne Skjølsvold summarized and discussed the available ^{14}C dates for the settlement of Rapa Nui. The results pushed the initial settlement forward from the previously established timeframe of AD 300–500, based on excavations at Poike ditch (Smith 1961a), to a date of the initial colonization around AD 800–1000 (Skjølsvold 1993: 94, 1994: 107; Martinsson-Wallin 1994; Martinsson-Wallin and Crockford 2002: 256). Roger Green (1966: 6) had previously suggested that linguistic evidence showed archaic traits in the Rapa Nui language and that the AD 300–400 date supported his linguistic model. In a paper delivered at the "Segundo Congreso Internacional de Arqueologia de Isla de Pascua y Polinesia Oriental" in Hanga Roa October 17–21, 1996, Green stated, based on Skjölsvold's re-assessment, that Rapa Nui was settled "from the Pitcairn – Mangareva region at circa 800 A.D." (Green 1999: 109). At the same conference, we stated; "The result of the excavations show continuous traits of human activity in Anakena from c. AD 800-1000 and up to modern times" (Martinson-Wallin and Wallin 1999: 182).

About 15 years after our excavations at Anakena, Terry Hunt and Carl Lipo investigated the dune to the northeast on the seaward side of *ahu* Nau Nau (Hunt and Lipo 2006). In accordance with our earlier investigation, they found cultural debris just on top of the bedrock at a depth of 345 cm. They evaluated dates from the early settlement in Anakena according to the "radiocarbon hygiene" criteria (Spriggs and Anderson 1993) and concluded that Anakena (and Rapa Nui) was settled around AD 1200 (Hunt and Lipo 2006).

In 2007, we carried out a re-dating project of the main trench (called C1) at Anakena from our excavation in 1987 (Skjølsvold 1994: 21–26; Wallin et al. 2010). The aim was to use the "radiocarbon hygiene" protocols and date samples from short-lived organic material such as nutshells and bones of the Polynesian rat (*Rattus exulans*). The conclusions reached from this work were that the cultural layer found on top of the bedrock under *ahu* Nau Nau on the inland side of the monument was disturbed during the initial construction phase of the large restored *ahu*. The bottom dark brown clayey layer with cultural debris was re-dated to c. AD 1000–1300 and the building phase of the first megalithic *ahu* Nau Nau was estimated to be around AD 1300 (Wallin et al. 2010: 43). Subsequently, Wilmshurst et al. (2011) carried out a general re-dating of the colonization of East Polynesia and they suggest that the earliest settlements of Central East Polynesia (Society Islands) are set at AD 1025–1121. The Rapa Nui initial settlement was proposed to be within the timeframe of AD 1200–1258 (Wilmshurst et al. 2011: 1818). This converges with a study by Mara Mulrooney (2013) on the chronology and land use of Rapa Nui suggested a "permanent and widespread settlement on the Island by at least AD 1200, with initial colonization possibly having occurred significantly earlier" (Mulrooney 2013: 4386).

The earliest cultural activity at Anakena found c. 3 m below the present surface, within a dark brown clay just on top of the bedrock, is still, after more than 30 years of research, the earliest dated settlement activity on Rapa Nui. So far, excavated samples from this context have yielded 11 early dates. Seven of the ^{14}C dates were done by the Kon-Tiki museum (Skjølsvold 1994; Wallin et al. 2010), two by Hunt and Lipo (2006) and three by Steadman et al. (1994). Radiocarbon dates of short-lived species (nutshells) as well as bones of the Polynesian rat and charcoal material from this layer have been dated. In a recent paper by DiNapoli et al. (2020), they evaluate these published ^{14}C dates (using the protocol for radiocarbon hygiene and Bayesian statistics) and estimated the time of initial colonization at AD 1150–1290 at 2σ. Furthermore, based on ^{14}C dated samples and the sample proveniences within *ahu* structures, Martinsson-Wallin et al. (2013) suggest the start of the building phase of *ahu* structures to c. AD 1300–1400 (Martinsson-Wallin et al. 2013: 412). DiNapoli et al. (2020) suggest the initial *ahu* construction phase to c. AD 1350–1450 at 2σ.

1.2 Rapa Nui Ritual Space: Ahu/Moai Concept

Several researchers have suggested that the *ahu/moai* concept is a materialized institutional ideology and have discussed the socio-cultural relationships, ritual connotations and development with changes and additions of various ideological/ritual built expressions (see Ayres 1975; Martinsson-Wallin 1994). An example of this is mentioned by McCoy (1976) and Martinsson-Wallin (1994: 72), who suggest that vertical standing stones in the rear wall of some *ahu* are an early architectural trait on Rapa Nui. Recently, Vogt and Cauwe (2019) discuss upright stones as a significant Rapa Nui ritual feature and a phenomenon with a longstanding significance. Martinsson-Wallin (1994) used relational statistics of various features connected to the ritual place in combination with radiocarbon dates and stratigraphy to show that ramps, wings and red lintels attached to the inland *paenga* platform facing are additions to the *ahu* structures over time. Mulloy (1961: 104–105), Smith (1961b: 213), and Martinsson-Wallin (2000: 49) furthermore suggest that statues were placed on the courtyard of the early monuments instead of on top of them. In a recent publication, Ayres et al. (2019) re-analyze some excavated *ahu* structures and compared the monuments with features and traits of East Polynesian ritual sites (*marae*). They suggest that these traits were included in early Rapa Nui *ahu* architecture. They argue for “vertical slabs, small, low platforms with small basalt images” in the period from initial colonization and up to AD 1400 (Ayres et al. 2019: 286). They further suggest that the development continued by a “Transformation of Marae into *Ahu moai* focus” in the period AD 1400–1700 (Ayres et al. 2019: 286).

The first part of the model by Ayres et al. (2019) is so far not confirmed by any securely dated *marae*-like structures from the AD 1150–1300 period on Rapa Nui. However, in light of research on the chronology of Rapa Nui initial colonization and subsequent development of ritual architecture, it is very likely that early ritual space featured upright stones. With this in mind and with the re-assessment of Rapa Nui and the Anakena chronology (DiNapoli et al. 2020; Wallin et al. 2010), our aim is to re-analyze the early activity area, called Nau Nau East at Anakena (Martinsson-Wallin and Wallin 1994: 123–211). This area is located about 50–75 m to the east of the present *ahu* Nau Nau at Anakena. Two radiocarbon dates on charcoal samples from Nau Nau East, one from a refuse pit and another from the cultural layer, show this to be an early activity area (Skjølsvold 1994: 106) (see dating details below). This suggests that the site is contemporary with the initial Rapa Nui settlement phase.

2 Nau Nau East: An Early Ritual Space

Initially, the activity area Nau Nau East was interpreted as an attachment to the initial phase of *ahu* Nau Nau (Martinsson-Wallin and Wallin 1994; Martinsson-Wallin 1994: 200–201). Due to the dating re-assessment for the initial settlement of Rapa Nui (c. AD 1150–1290), compared with the date of Nau Nau East, we have re-interpreted this area to be a ritual space associated with the initial settlement of the island pre-dating the earliest date of *ahu* Nau Nau. We suggest that Nau Nau East is an early expression of ritual practices that existed in the Central East Polynesian area from where the Rapanui originated. The features and remains found at Nau Nau East have already been described in detail and interpreted as a ritual space by Martinsson-Wallin and Wallin (1994: 127–141, 1999: 184–185, 2000: 30–31), but here we present a closer investigation of the different features observed at the site to explore early ritual relationships.

In this paper, we are going to reassess, clarify and contextualize the actions and practices found at the site (Fig. 6.3) and how they demonstrate the occurrence of ritual behavior. We use data retrieved from archaeological research, ethnohistory and traditional history for Rapa Nui and Polynesia to argue that the activity area Nau Nau East is an early ritual space that shows connections to similar sites in other East Polynesian islands (Kirch and Green 2001).

2.1 Place

Firstly, we give attention to place and the landscape setting on which Nau Nau East is located. Anakena in traditional settlement history is suggested to be the first landing place of the founding chief, *Hotu Matua,* who stepped ashore at the beach at *Hira Moko* (Anakena). According to traditional history, it is narrated that; “*Inei te ariki ana noho kona rivariva*- Here the king will live in a fine place” (Metraux 1940: 59). The activity area Nau Nau East is situated at the foot of the hill called *Maunga Auhepa* or *Maunga Hau E’epe* (Smith 1961c; Routledge 1919) overlooking the beach and this early habitation site is located close to a stream that had its outlet on the west side of the bay. The placing of Nau Nau East, behind (sacred) and higher than the early settlement (found under *ahu* Nau Nau) by the sea (profane),

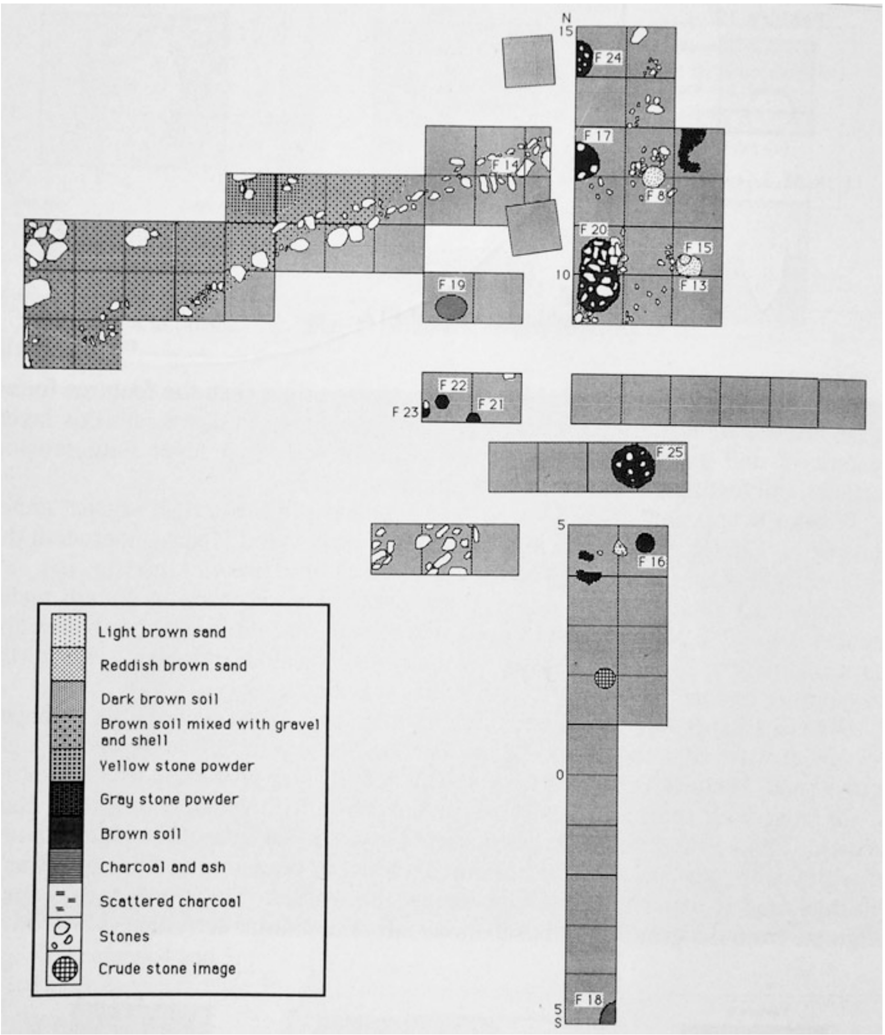

Fig. 6.3 Plan drawing of the site Nau Nau East with features indicated (from Martinsson-Wallin and Wallin 1994: 134)

can be interpreted in the Polynesian binary opposition perspective in the following binary oppositions, such as: back:front::high:low::sacred:secular::chief:commoners (Ottino 1990: 8).

The initial settlement activity beneath Ahu Nau Nau I consisted of a cultural layer, including a simple hearth, located close to the seashore just above the bedrock. Zoosteological analyses of bone refuse from the early layer show that sea mammal hunting and deep-sea fishing were of importance during the initial phase (Martinsson-Wallin and Crockford 2002; Steadman et al. 1994). This near seashore location placed *low,* and being in the *front* of the bay, is interpreted as an area where people carried out their daily chores in the world of the living. Nau Nau East on the other hand is placed on a *high* position in the *back.* This is a position associated with ritual sacred actions executed by chiefs and priests/specialists. A secluded location close to the hillside is a logical place to establish an initial Polynesian ritual space. It was a place for the chiefs to control the people and to keep the connection to the ancient gods and ancestors, but still not too far away from the ordinary habitation area. Excavations by Skjølsvold at the artificially levelled top of the Auhepa hill did not find any built stone architecture, although large quantities of charcoal were found, which may have a ritual connection. However, Carlyle Smith interpreted it to be a site of defence (Smith 1961c: 277–278).

2.2 Time

In the sand layer that covered Nau Nau East, we found cultural debris, including artifacts and hearts, bones as well as a human burial that we (after examination) left in the ground and covered up with sand. One of the features (F5), a fireplace, was dated and proved to be modern in origin. However, in this fireplace, a small rounded burnt obsidian disc was found that we interpreted as an eye pupil that possibly indicated the burning of a *Moai Kava-Kava*. These activities are hypothesized to be tied to the final settlers of Anakena at the end of the nineteenth century, and the burning was possibly influenced by the early Missionaries (Martinsson-Wallin and Wallin 1994: 177). Fire damaged rongorongo tablets and wooden bird images may indicate the burning of ritual objects on Rapa Nui (Heyerdahl 1976: 46–47, Plate 135 b, c). Destruction of ritual objects by missionaries on Rapa Nui is also mentioned by Jaussen (1893: 12), and Rapanui natives told Paymaster Thomson (1889: 514) that:

> the missionaries had ordered all that could be found to be burned, with a view of destroying the ancient records, and getting rid of everything that would have a tendency to attach them to their heathenism, and prevent their thorough conversion to Christianity.

Such acts are also described in other Polynesian islands in the early nineteenth century. The burning of idols probably ended the use of a main *marae* in the Society Islands around 1820 (Tyerman and Bennet 1831, vol 1: 266–267).

Below the sand layer, a cultural layer was discovered that consisted of a 40–60 cm thick dark brown clayey soil. Below this was a sterile reddish-brown soil (for plan drawings, see the excavation report in Martinsson-Wallin and Wallin 1994). The cultural layer was dated by two charcoal samples, one from the bottom of the cultural layer (T-7345, BP 810 + −80, AD 1048–1058 3.9%, *1140–1394* 91.6%), and one from a refuse pit (F25) (T-7346, BP 810 + −70, AD 1052–1082 2.0%, *1148–1325* 83.8%, 1346–1391 9.6%, Cal. 2σ). Calibrated with a Pooled Mean, the two samples indicate a date of c. AD 1197–1297 (Cal. 2σ). (All samples discussed in this paper are calibrated by using OxCal 4.4, SHCal 20.) These two dates are not sourced to a specific species, but collected from different contexts from the same cultural horizon and gives a unified chronological outcome. More materials were saved that can be used for analyses in the future.

2.3 Material Culture and Features

2.3.1 Crude Stone Image (for Location see Fig. 6.3)

At the southern end of the Nau Nau East area excavation, a crude anthropomorphic upright stone image (Figs. 6.4 and 6.5) made of Rano Raraku tuff was found standing. It is 70 cm high. The diameter of the "head" is c. 30 cm, the mid part or "stomach" has a diameter of c. 48 cm and the diameter at the base is c. 20 cm. It therefore has a somewhat elliptical shape. The top of the head is flat, and the base is rounded. An incision divides the head and the body. Two grooves mark the eyes and two knobs in relief shape the ears. The arms are vaguely noticeable, extending along the sides and turn in an angle to join in front of the stomach (Martinsson-Wallin

Fig. 6.4 The crude image stone upright in situ during excavation. Photo: Helene Martinsson-Wallin

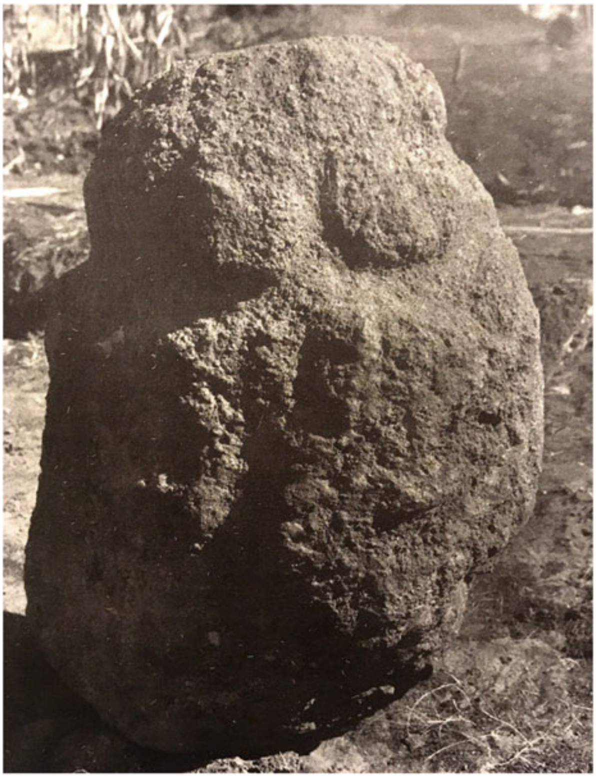

Fig. 6.5 Crude image stone upright. Height of the upright is 70 cm. Photo: Arne Skjölsvold

and Wallin 1994: 139–141). The anthropomorphic characteristics of the image are visible but very rudimentary.

The image is firmly seated at the bottom of the cultural layer and was partly buried in the dark brown clayey soil. The sandy layer had subsequently buried the image, and the flat top of the head was only partly visible before excavation. Small simply carved images exist in Rapa Nui, and are, for example found incorporated into later *ahu* structures (Martinsson-Wallin 2000). Such simple images occur in the Society and Tuamotu islands, as guardian images (stone *ti'i*) standing at the boundaries of the ritual space (Emory 1933: 17). Skjølsvold (1965: 101–102) reported a small stone image at a ceremonial enclosure called *Te Rae Rae* on the island of Raivavae, which resemble the one at Nau Nau East. One obsidian core and a few obsidian and basalt flakes were found further south on the inland side of the crude upright image, indicating cultural activity in that direction. The crude image might have been erected there to act as a “guardian” of the ritual space.

2.3.2 Stone Construction/Demarcation (Feature 14, for Location see Fig. 6.3)

In the north part of the excavation area, we found a stone row that formed a c. 8.5 m long demarcation or boundary (Fig. 6.6). It was oriented in a northeast to a southwest direction and made up by two parallel rows of unworked stones of varied size (5–50 cm) (Fig. 6.7). The stones were found embedded in the dark brown cultural layer. The southwest end was probably partly disturbed due to excavations/restoration work at Anakena carried out in 1978–1979 (Martinsson-Wallin and Wallin 1994: 136). The soil on each side of the demarcation had a different composition. On the northern side (seaside), the soil was mixed with gravel, shell and a small amount of water-worn obsidian was noticed. This material seemed to be material collected from the seashore. Associated with the stone demarcation and positioned just on top of the dark brown soil, we noticed an area of about 1 × 2 m in size, with pieces of

Fig. 6.6 Stone row demarcation looking towards the northeast. Photo: Helene Martinsson-Wallin

Fig. 6.7 Detail of stone row demarcation. Length of this part of the stone demarcation is 4 m. Photo: Paul Wallin

red scoria and a "yellow stone powder". These materials could have been a result of different stone working activities but considering the superposition at the site, these activities probably were of a later date than the earliest activities. On the south side (inland side) of the stone rows, the dark brown cultural layer was undisturbed (Martinsson-Wallin and Wallin 1994: 136).

The double row of stones is interpreted as a support for planks/poles or some kind of wooden fence. The field observations suggest it was excavated down on the north side, and then the planks were set into the ground and supported by a fill of stones and gravel from the beach. The construction indicates that this area may have been fenced in and divided or marked out in some way. However, there were no traces of wood among the stones indicating they have been removed in prehistoric times.

2.3.3 Postholes (Feature 21, 22, 23 and 15, for Location see Fig. 6.3)

Three postholes (F21, F22 and F23) were found in the cultural layer at 1 m in depth from the surface within a limited space of one square metre. They were situated three metres south of the stone row demarcation and six metres north of the crude upright statue. The postholes were rounded, c. 25 cm in diameter, and they penetrated into the underlying sterile soil (Martinsson-Wallin and Wallin 1994: 137). The stratigraphy indicates they belonged to the early dated activity at the site, and that they would have supported solid posts, but their close spacing does not indicate structural posts for a house. Instead, the post positioning may have been uprights or foundations for sacrificial altars, or that the posts might have been wooden idols/god images. An additional single posthole (F15) was found c. five metres to the northeast of these posts and is described under special activities below.

2.3.4 Hearths (Feature 18 and 19, for Location see Fig. 6.3)

We found two hearths in the area. Feature 18 was 50 × 50 cm in size, 5 cm thick, and consisted of a bowl-shaped stripe of soot and charcoal found 35 cm beneath the surface of the dark brown cultural layer. It was located at the periphery of the site near the very south end of the excavated area and about seven metres towards the inland side of the crude upright image. It contained a few obsidian and basalt flakes, and a coral file of a long triangular type but no bones indicating the hearth was used for cooking (Martinsson-Wallin and Wallin 1994: 137, 178). The other hearth, Feature 19, has a central position in-between the row of stones and the three central postholes. It was comprised of a 60 × 60 cm large lens of soot found about 15 cm down into the dark brown cultural layer. No bones or artifacts were associated with this feature (Martinsson-Wallin and Wallin 1994: 137, 178).

Fires are of course used for cooking but fire is also of importance in Polynesian rituals since the act of burning was believed to destroy evil spirits. Fire also cleaned the space and was part of the healing process of sick persons (Handy 1927: 245–247). Fires on *marae* courtyards are also common in the Society Islands (Wallin and Solsvik 2010: 74). In ethnohistorical accounts, it is mentioned that fires were lit close to the statues (Roggeveen, 1722) and are evident in crematoria with burned human remains associated with *ahu* sites. Further evidence for the ritual use of fire comes from the legend about the people called *hanau momoko* that killed the people called *hanau eepe* by driving them into a ditch with fire. This supports the idea that fire is essential and probably has to do with sacrifices (Metraux 1940: 69–80). In addition, a small hearth was found by us on a large flat stone within the fill of *ahu* Ra′ai to the east of Anakena and dated to AD 1316–1456 (Cal. 2σ), (Ua-13165, BP 570 + −50). Similarly a burn area under the ramp of *ahu* Heki'i dated to AD 1270–1310 (Cal 2 σ), (Ua-11700, BP705 + -45) (Wallin and Martinsson-Wallin 2008). The dates fall within the early phase of *ahu* construction, in line with *ahu* Nau Nau I, and indicate the continuous importance of fire in the ritual behaviour of the Rapanui (Wallin and Martinsson-Wallin 2008: 146).

2.3.5 Refuse Pits (Feature 17, 20, 24 and 25, for Location see Fig. 6.3)

Four rounded pits were found in a row with pit F24 on the north end and pit F25 on the south end at a distance of about 2–3 m from each other. All pits were found at a depth of 70–100 cm below the surface and about 30–50 cm from the surface of the brown cultural layer. The diameters vary between 60–85 cm and they all have straight sides and a flat bottom. F20 consists of two merged pits and is in the shape of a figure eight and the total size is, therefore, 75 × 135 cm (the southern part of the pit is deeper than the northern part) (Fig. 6.8). The depth of the pits varies between

Fig. 6.8 Refuse pits F25 to the left and F17 to the right. View towards west. The horizontal length of the trench is 4 m. Photo: Paul Wallin

80 cm (F17 and F24) and 130 cm (F20 and F25). The fill in each feature consisted of loose brown soil from the site but the stones (c. 10–50 cm in size) of basalt, scoria and pumice tuff were brought from elsewhere and intentionally deposited within the pit. Some were from the beach. Such repeated behaviour could point to ritual actions (Martinsson-Wallin and Wallin 1994: 137–139). F20 and F25 include obsidian and some basalt flakes as well as a few artifacts and bones from dolphins, seals, sea birds, fish and shells.

There are no traces of fire or fire-cracked stones in F17, F20, F24 and F25, but F25 included some charcoal that was dated (see details above). The dated refuse pit (F25) contained 860 bone elements of the Polynesian rat (*Rattus exulans*), indicating an MNI (minimum number of individuals) of 76 (49 adult and 27 juvenile). There were also 160 skeletal elements from sea mammals (Dolphin, *Delphinidae sp.*) (Martinsson-Wallin and Wallin 1994: 211) indicating hunting at sea, an activity more common in early contexts and may explain the harpoon (see Fig. 6.11 below) found at the site (Martinsson-Wallin and Crockford 2002; Wallin 1996). F24 included no bone remains (Martinsson-Wallin and Wallin 1994: 126, 137, 178).

All the features have great similarities in position, size, as well as their stone fill with loose soil. Feature 20 and F25 are the most complex, with stone flakes and other materials (Fig. 6.8). In F20 we observed marks from a c. 5 cm wide digging stick on the inside of the pit wall. This indicated that the infilling of the pit happened just after their excavation since the fragile traces of the digging stick were clearly visible and unweathered. At ceremonial sites in Central East Polynesia associated refuse pits, or refuse heaps, were common. These were places for the deposition of material used when performing rituals (Emory 1933: 14; Wallin and Solsvik 2010:

60). We suggest that the content in the pits at Nau Nau East are left-over building materials, food consumed during building activities, and from tools used at certain ritual/building actions at the site.

2.3.6 Grinding Residues/Special Activities, (for General Location see Fig. 6.3)

Other special activities are found in three areas. The first of these special activity areas (no. 1, Fig. 6.9) was located about 1 m to the east of the refuse pits F17 and F20. It consists of an area with two rounded, large pits c. 40–60 cm in diameter (F8 and F13). They were both about 30 cm deep and filled with light brown sand. The only object associated with the pits was one obsidian flake. However, towards the bottom of F13 a posthole (F15 c. 20 × 20 cm in diameter) was detected. It was v-shaped, 20 cm deep, and filled with light brown sand. A hammerstone of basalt was found in the sand fill of F15. In the immediate area were scattered c. 10–15 cm large basalt stones and spots of red ochre (*ki'ea*) as well as an irregular area of grey stone powder that may have originated from the shaping/polishing of basalt stone adzes or other tools (Martinsson-Wallin and Wallin 1994: 133). The posthole indicates a single standing post at a similar distance from the stone demarcation (F14) as the other posts (F21, F22 and F23). This post (similar to upright stones) probably has a special meaning for this activity area (Kirch and Green 2001).

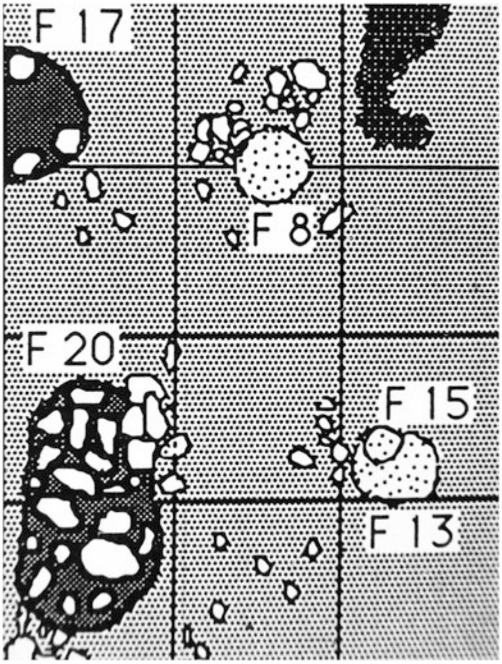

Fig. 6.9 Detail of plan drawing showing special activity area 1. Excavation units are 1 m^2

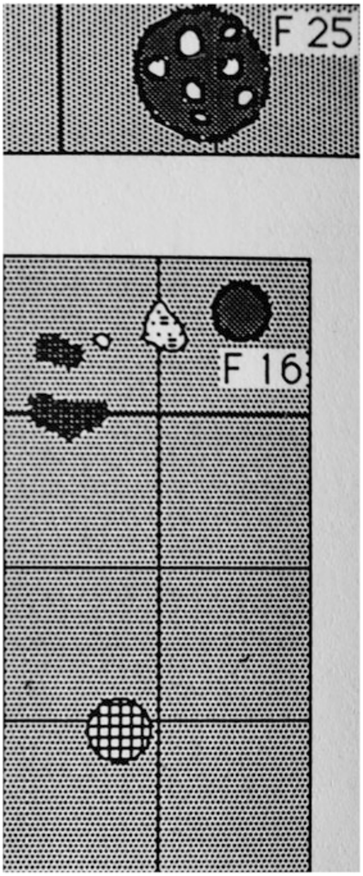

Fig. 6.10 Detail of plan drawing showing special activity area 2. Excavation units are 1 m^2

The second area (no. 2, Fig. 6.10) was located c. 1 m south of F25 and about two metres north of the crude image upright. In this area, F16, a rounded 40 × 40 cm pit, 20 cm deep and filled with loose brown soil was found 30 cm below the surface of the dark brown cultural layer. It contained a few obsidian flakes (Martinsson-Wallin and Wallin 1994: 136, 178). The function of this pit is uncertain. Within this area, there was also a smaller pocket of light brown sand and two smaller areas of grey stone powder similar to the stone powder found in special activity area no. 1.

The third area (no. 3, see Fig. 6.3) shows that this activity was located 3–4 m west of the second area just described. It consisted of an area with scattered stones 10–40 cm in diameter, which were unusual objects to find in the brown cultural layer. If the stones were from a specific construction, or part of a pavement, it could not be determined during the excavations (Martinsson-Wallin and Wallin 1994: 134).

3 Spatial Analyses of Artifacts, Obsidian/Basalt Flaking and Bone Remains

We suggest that the portable artifacts and bones found in this area can be interpreted in relation to the features described above, which differs from the remains found in ordinary cultural layers. The obsidian, stone debris, and sea mammal bones are concentrated in the area of the refuse pits and can be understood as habitus driven. Other artifacts are unique or found in concentrations. We will start this section with a discussion of some of the specific finds. (Based on our report Martinsson-Wallin and Wallin 1994).

The small bone harpoon head is the only one so far found in Rapa Nui (Fig. 6.11). The harpoon was recovered in the early cultural layer on the inland side of the stone demarcation (F14). In addition, one unfinished basalt fishhook and one fishhook of bone (only the shank) were found in the cultural layer. The stone fishhook was found in association with the special activity area no. 1 and its production might have occurred here, as indicated by the basalt stone powder in this area, but since it is broken and unfinished, it could have been intentionally deposited close to the anthropomorphic image. Stone hooks have been found in excavations of houses

Fig. 6.11 Harpoon head. The harpoon is 6.04 cm long and 1.27 cm wide at the central hole location. Photo: Paul Wallin

(*hare paenga*) in the vicinity but they represent later types than the one found here (Smith 1961c: 283).

Two small obsidian disks found in the early dated layer were interpreted as pupils from wooden statues. One was recovered from special activity area no. 1 and the other just 1 m from special activity areas no. 2 and no. 3. Another group of rare artifacts are pendants of bone. One was found in the same excavation unit as the harpoon and three others within 1–2 m to the east of that location in a small cluster. Two other pendants were found in the special activity areas no. 2 and no. 3.

Bone fishhooks have been found in other excavations, but here the only one was found in association with the small upright stone image. The bone needles were found close to the central postholes and one was associated with special activity area no. 2. Four grinding−/whetstones were found within 1 square meter unit about 1 m south the special activity area no. 1, in which the grey stone powder was found. This might explain the occurrence of the grinding stones/whetstones at this location. One other grinding−/whetstone was also found about 1 m north of the grey stone powder in special activity area no. 2. Finally, six hammerstones were found in a cluster just to the east of the large refuse pit (F20), which is located in an area rich in obsidian and basalt flakes. Two hammerstones were found close to the central postholes. This was another area with high amounts of obsidian flakes. Other artifacts like chisels, adzes, scrapers, knives, drills and files were more commonly encountered and spread evenly in all areas with few identifiable concentrations. Noteworthy is the occurrence of 17 coral files found in connection with F20. These artifacts can be tied to different crafts, such as the making of wooden images carried out in this early ritual context.

Large quantities of obsidian, basalt and bone remains were found in almost all the excavation units. However, the most intensive area for obsidian flakes, fragments and cores (as well as basalt flakes) surrounded the refuse pits F20, F17 and F24 located in the north part of the excavation (see area indicated in Fig. 6.12). The pits with refuse are suggested to be part of a ritual habitus and as such, we interpret that they also attracted other waste materials.

We identified the bone remains to different species such as dolphin, seal, sea mammal, rat, bird, fish, crab/lobster, sea urchin, chitons (*plaxiphora)* and shells (For detailed osteological analysis, see Martinsson-Wallin and Wallin 1994: 203–211). In addition, we identified a few scattered human remains in the dark brown cultural layer. The crabs/lobsters and sea urchin spines were found spread over the entire excavated area but in small amounts. Shells and chitons were more common and evenly spread as well, with concentrations of shells in the western part of the stone demarcation (They were possibly fill material collected from the sea). Another concentration of shells was found close to the central postholes and in special activity area no. 2.

The amount of fish bones was limited to 1–70 g per excavation unit and evenly spread throughout the cultural layer. Bone material from sea mammals, mainly dolphins but also leopard seals, were found in the northern part of the excavation within a c. 12 × 5 m large area (see Fig. 6.12). This can perhaps be seen as an area for sacrifices and depositing of bones from ritual meals or feasting. Dolphins and

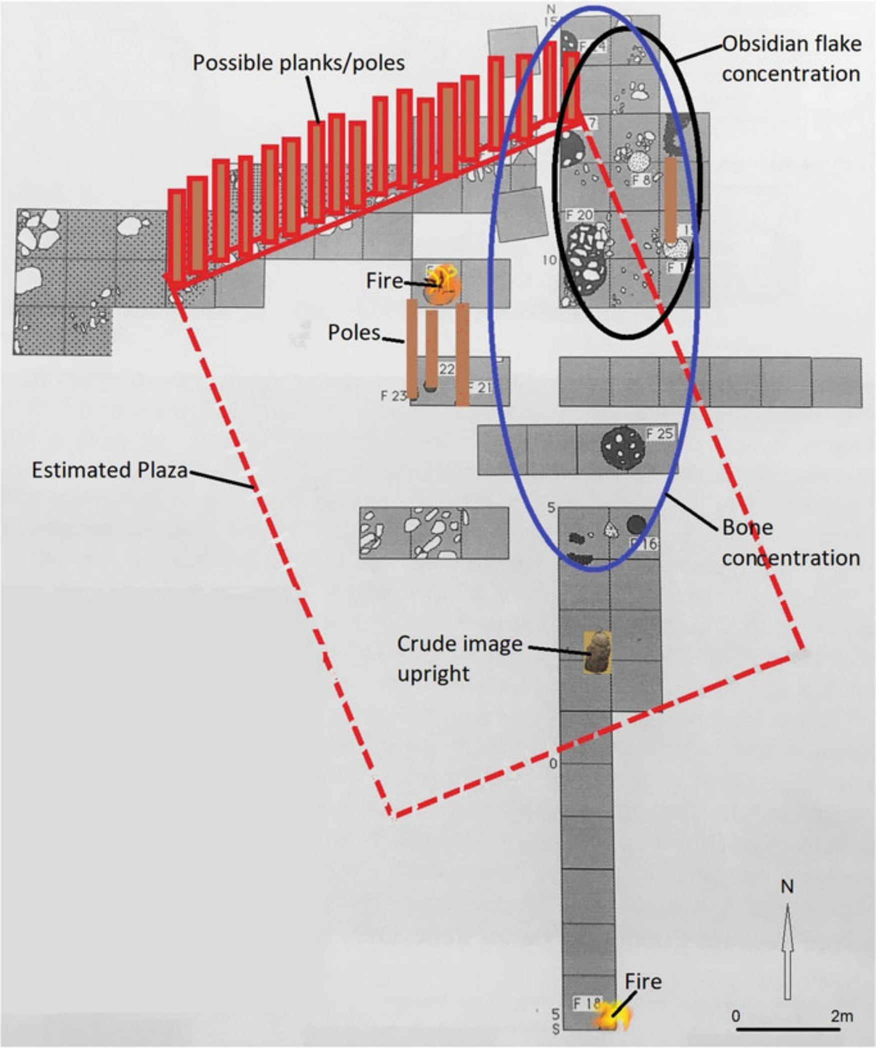

Fig. 6.12 Reconstruction model of early ritual site features and activities. Drawing: Paul Wallin

seals are probably status food for the chiefs that probably was occasionally taboo for ordinary people (Ayres 1975).

Only six discoveries of human remains were recovered in the cultural layer. They were distributed in five different locations, in special activity area no. 3, by the central postholes, and next to F20 and F17. The bones included two teeth (one from a child and one adult), a part of a fibula leg bone, as well as three hand and finger bones. Human bones in ritual places are common and usually derived from loss during different treatments of the dead that may be ancestors, sacrifices, or enemies (Handy 1927: 132–135; Wallin and Solsvik 2010).

4 A Reconstruction Model of the Ritual Space

Based on the early dating of the cultural layer and the observed components found at Nau Nau East, we interpret this site as an early ritual space (Fig. 6.12) that was created by Early Central Polynesian ritual activities. The object that defines the place as special is the stone upright with crude anthropomorphic attributes. Other important features are the three centrally located postholes that indicate upright wooden poles. Such poles are described at ritual sites of the Maori in New Zealand (*pouahu*), which marked the sacred place for various rituals (Best 1925: 724). In addition, wooden posts or images are associated to the *heiau* in Hawai'i (Valeri 1985: 243). A fourth posthole indicating a post placed in a central position in special activity area no. 1 was surrounded by large amounts of sea mammal bones as well as obsidian flakes. This post may indicate a place of ritual activities and "holy" refuse. The stone demarcation that we interpret, as a foundation for planks, could be the location for something like the *unu* planks observed in Tahiti. There, the planks indicated the practice of human sacrifices at the site (Handy 1927). In Hawai'i, Valeri (1985: 238) and Kamakau (1961: 202) mention a fence consisting of planks and poles separating the ritual area from the exterior.

Hearths, or fire, as well as dispersed human remains, are indicative of ritual actions involving cleaning, clearing and sacrifices (Handy 1927: 238–239; Henry 1928: 172, 204; Palmer 1868). Traces of fires and scattered charcoal as well as human bone remains were regularly found during excavations of several *marae* courtyards in the island of Huahine in the Society Islands (see for example Wallin and Solsvik 2010: 33, 49, 57, 74, 79). As evidenced by past research on Rapa Nui, fire and cremations later became a widely spread ritual action as indicated by the many crematoria tied to the image *ahu* structures (Martinsson-Wallin 1994: 102). Roggeveen (1722: 15) also reported that the Rapanui lighted fires at their *ahu* structures.

The refuse pits, as well as sea mammals and mainly obsidian knapping and basalt grinding/polishing, are concentrated within the northeast of the excavated area. The debris could be from ceremonial feasting, the manufacturing of tools and deposition of tools used within the ritual space. That artifacts such as adzes were brought and stored at ritual spaces followed by a feast are described for the Society Islands. Such actions gave *mana* to the adze before it was employed to cut down trees used in the building of canoes (Henry 1928: 146–147).

The special activity area no. 2 was located just 2 m to the north in front of the upright stone image, which is a similar setting to the activities in special activity area no. 1. They also have the same position in front of the upright wooden post/image in that area. Images and posts are signs of sacred locations for sacred actions (Handy 1927: 191).

5 A Spatial Model of Settlement and Ritual Activities at Anakena

According to Skjølsvold (1994), the main aim of the archaeological excavations at Anakena was to investigate *ahu* Nau Nau and its phases of construction and use. An additional aim was to make exploratory trenches in the terrain surrounding the *ahu* to gain knowledge of the prehistoric settlement developments and activities at Anakena bay (1994: 5). Therefore, 23 trenches of varying size were excavated in the surroundings of Anakena, including the activity area of Nau Nau East (Skjølsvold 1994: folded map).

5.1 Settlements

Settlement activities were detected at several locations at Anakena (Fig. 6.13), which gives a good overview of the habitation area and how it changed over time. The settlement activity of greatest interest is the one found just in front of and on the seaside of *ahu* Nau Nau. The earliest activities were evidenced by cultural remains in a dark brown clayey soil at a depth of c. 3 m; just on top of the bedrock. After its discovery in 1986–1987, this activity area has been investigated two additional times; by Steadman et al. (1994) and by Hunt and Lipo (2006). All three investigations returned the initial dates of the site to around BP 900. This resulted in an estimated calibrated age of around AD 1150–1290 (DiNapoli et al. 2020). It is the earliest dated site on Rapa Nui.

A cultural deposit of 45 cm in thickness and found at a depth of about 75 cm from the present surface in "trench M" was located c. 110 m southwest of *ahu* Nau Nau. The layer consisted of brown soil with spots of charcoal, cultural remains and water polished stones indicated a nearby stream (Skjølsvold 1994: 75). This deposit has been dated to AD 1146–1407 (Cal.2σ), (T-7977, BP 780 $+ -90$). The data was derived from a single sample and not determined to species. The occurrence of activity at this time period is interesting since the excavation shows that a permanent stream once had its outlet here. The remains point to early settlements and activities close to the stream and beach.

In addition, there are dated samples from other activities/settlements found in trenches excavated in the close proximity to *ahu* Nau Nau that document the age of past constructions. For example there is a cultural layer called the "upper cultural layer" in trench E, K and A found on the seaside of *ahu* Nau Nau. This layer was dated to around AD 1250–1400 (Skjølsvold 1994: 106). *Ahu* Nau Nau I c. AD 1300–1350 was constructed on top of this earlier settlement activity. An additional but later dated layer with cultural remains such as animal bones, some obsidian and coral files were found at a depth of about one metre c. 75 m to the southwest of *ahu* Nau Nau (Trench "C86"). A charcoal sample found in a defined cultural layer lens has been dated to c. AD 1417–1688 (Cal. 2σ) (T-6680, BP 370 $+ - 90$). There

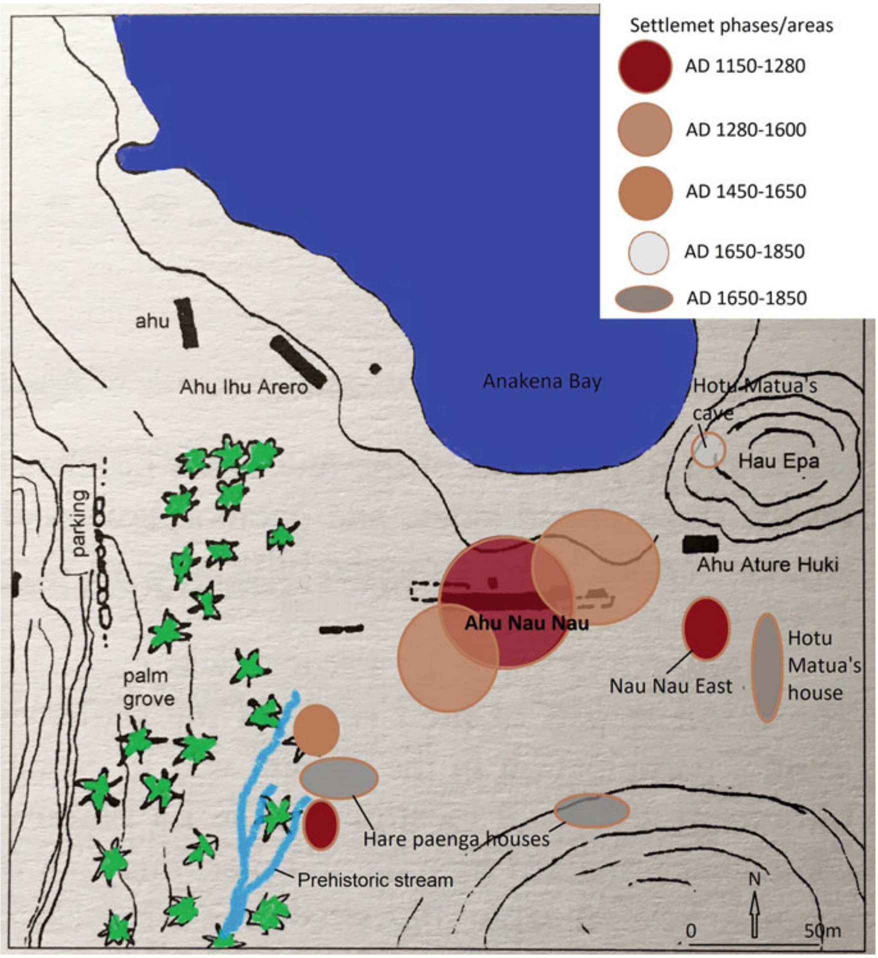

Fig. 6.13 Interpretation of settlement site actions at Anakena. Drawing: Paul Wallin (Based on figure in Martinson-Wallin and Wallin 2000: 27)

are also indications of high-status boat-shaped houses (*hare paenga*) found on the slopes around *ahu* Nau Nau of, which the largest and most intact is called Hotu Matua's house. They probably date from the period AD 1650–1850. In one of them was found a blue glass trade bead that very likely is one given to the Rapanui by some of the early Europeans like the Dutch in 1722. In addition, late activities are tied to the so-called Hotu Matua's cave (Skjølsvold 1961: 273–275) on the seaward side of the *Maunga Auhepa* hill, which has an artificially flattened top that was investigated in 1955–1956 as mentioned above (Smith 1961c: 277).

5.2 Ritual Spaces

We have suggested that the location and function of the activities at Nau Nau East are associated with ritual activities that date to around AD 1200, which so far is the earliest ritual space excavated and dated on Rapa Nui. Based on the extensive excavations in the Anakena sector during 1986–1988 we will discuss the development of the ritual spaces for this area (Fig. 6.14).

A re-assessment of the initial building phase of *ahu* Nau Nau was carried out in 2007 when the main trench excavated in front of the *ahu* was re-dated (Wallin et al. 2010). Skjølsvold initially argued, based on two dated charcoal samples, that the early phase of *ahu* Nau Nau dated to around AD 1200 "or a little earlier" (Skjølsvold 1994: 107). However, new dates on charcoal samples from the earliest stage of the paved plaza floor, and a sample found just immediately below the pavement of the plaza, gave a date range of c. AD 1285–1450 (Cal. 2σ) (Ua-34184, BP 640 + −65) (Wallin et al. 2010: 43). All dated *ahu* structures on Rapa Nui are furthermore re-analyzed in another paper by Martinsson-Wallin et al. (2013). The conclusion is that the building of *ahu* structures began around AD 1300–1400 (Martinsson-Wallin et al. 2013: 412). This places the initial phase of *ahu* Nau Nau to c. AD 1300 or a little later.

When re-assessing Skjølsvold's dated samples (1994: 106, samples T-7974, T-7344, T-7350) that were derived from the "upper cultural layer" in trenches A, E and K, on the seaward side of *ahu* Nau Nau, they give a pooled mean date of c. AD 1317–1433 (Cal. 2σ). This means that this cultural layer is contemporary with the Phase I building of *ahu* Nau Nau. The shape of the first *ahu* was a single stone platform faced with unworked as well as nicely dressed c. one-metre high *paenga* slabs, with a paved courtyard in front (see Skjølsvold 1994: 27, Fig. 22). Small size statues of different shapes probably were erected on the paved plaza or courtyard.

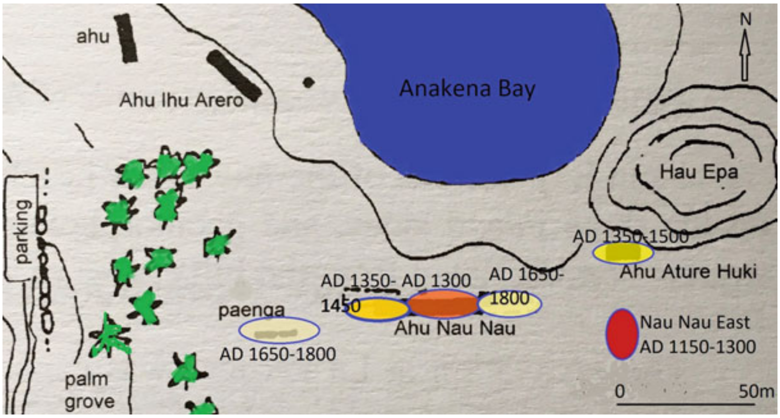

Fig. 6.14 Interpretation of ritual space and *ahu* site development at Anakena. Drawing: Paul Wallin (Based on figure in Martinson-Wallin and Wallin 2000: 27)

Fig. 6.15 Female statue found at Anakena. Photo: Paul Wallin

We base our argument on the presence of a smaller statue head of Rano Raraku tuff with round shape in the seawall of the present *ahu* and our finding of a basalt head of a female statue placed in the wing of the western side of the *ahu*. The body part of this statue had been found at Anakena in 1955–1956, and placed on display at the Kon-Tiki museum. In 1988 the body was brought back to Rapa Nui (Skjølsvold 1994: 88). This c. 167 cm high female basalt statue is now displayed at the local museum. The female basalt statue with its narrow shape reminds one of a basalt upright (Fig. 6.15). In conjunction with the finding of the female head, a torso of a smaller statue of red scoria was recovered. Estimating the missing head of this small red scoria statue puts the original height of this image at about 1 m (Skjølsvold 1994: 87–91).

Ahu Nau Nau Phase II, built of nicely dressed stones, is located to the west of *ahu* Nau Nau I. The latter was re-used as a wing during this second phase. *Ahu* Nau Nau Phase III is the presently restored *ahu* that has been dated with two charcoal samples. One gave a date of AD 1271–1485 (Cal. 2σ) (Ua-617, BP 610 + −85), and the other, which is a nutshell found just above the plaza floor of *Ahu* Nau Nau Phase 1 before soil covered it, gave a date of AD 1399–1455 (Cal. 2σ) (Ua-34,183, BP 535 + −35). Based on these dates, we suggest that the building of the restored *ahu* is around AD 1400. For stratigraphic/architectural reasons, the building of the Phase

II *ahu* is placed between c. AD 1350–1400. A final Phase IV of *ahu* Nau Nau is represented by additions of platforms to the east. A dated charcoal sample associated with a pavement that belonged to this phase gave a date of c. AD 1600–1880 (Cal. 2σ) (T-7976, BP 220 + − 80). Nicely dressed *paenga* indicating a structure c. 50 m to the west of *ahu* Nau Nau, was dated by a charcoal sample found in association with the *paenga* to AD 1625–1953 (Cal. 2σ) (T-7348, BP 200 + −80). This date is in line with the late Phase IV activities.

Ahu Ature Huki is located about 70 m northeast of *ahu* Nau Nau and about 50 m north towards the seaward side of the ritual activity area Nau Nau East. The structure only has one statue and we suggest that it is interpreted as a smaller junior branch addition to the main *ahu* Nau Nau (Martinsson-Wallin and Wallin 2014). Two trenches were excavated, one on the front inland side, and one at the seaward side. The pooled mean of two dates from these trenches gave a range between c. AD 1380–1497 (Cal. 2σ) (T-7979, BP 510 + −80, Ua-1144 BP 580 + −85), which corresponds to *ahu* Nau Nau Phase II-III. The time around AD 1400 seems to be a rather expansive phase in the history of Anakena and in the building of monumental architecture of ritual/ceremonial significance on Rapa Nui.

6 Discussion and Conclusions

Based on inter-site relationships of artifacts and features, stratigraphy, the provenience of re-assessed dated charcoal samples, as well as evidences from ethnohistory and traditional history, we have re-interpreted the area called Nau Nau East to be an early ritual site. We have in addition taken the methods of "radiocarbon hygiene and Bayesian statistics" into account when discussing the appearance of initial settlements in East Polynesia and Rapa Nui (DiNapoli et al. 2020; Mulrooney 2013; Wilmshurst et al. 2011).

Initially, we viewed the Nau Nau East site as an attachment to *ahu* Nau Nau I, since we then viewed the settlement of Rapa Nui to be 200 years earlier. However, additional dates and calibration methods (DiNapoli et al. 2020; Hunt and Lipo 2006; Wallin et al. 2010) have re-evaluated the initial settlement chronology for Rapa Nui. There are, as shown above, several dated samples found in the cultural deposits just on top of the bedrock and under and around the earliest phase of *ahu* Nau Nau that indicate an initial settlement to c. AD 1150–1290. The site called Nau Nau East is likely contemporaneous with these early activities at Anakena.

Using the updated chronological framework and the spatial relationship of the various activities at Anakena, we re-interpret the activity area Nau Nau East to be an early ritual space clearly showing a Polynesian connection. The site is demarcated by a small crude stone upright image as well as raised poles, planks, fires and refuse pits with concentrations of sea mammal bones, as well as Polynesian rat bones. These activities indicate feasting and perhaps sacrifices at the site, which fits well into the Polynesian ontology. These were the ritual features brought to the island by people from East Polynesia. Such similarities are not surprising due to a common origin and this has been pointed out before (Cochrane 2015), but the focus has mainly been on the architectural features of *ahu*/*marae* structures and not on adjacent activities. Below follows some examples from other sites in Rapa Nui and East Polynesia showing the use of these early ritual features.

In comparison, similar features have been found at the site complex located on the Terevaka volcano called *Ava Ranga Uka a Toroke Hau*. This complex is interpreted as a water and fertility sanctuary used by the elite (Vogt and Cauwe 2019). Part of the complex is an *ahu* with a single *moai*. Under the ramp, that according to the excavators dated to around AD 1300, was a crude partly worked upright stone found, which by its location seemed to antedate the ramp construction (Vogt and Cauwe 2019: 320–321). This potentially places the site in an early Rapa Nui ritual context. This upright stone might have been the original focal point of the fertility rituals at the site, like the small crude image upright at Nau Nau East and possibly other single uprights in different contexts found on the island could have had similar functions (see map in Vogt and Cauwe 2019: 323). We further suggest that the female basalt statue found at Anakena mentioned above, and other smaller statues, are tied to early ritual activities, since they often have been mutilated and re-used/incorporated into later ritual architecture as observed in several places on Rapa Nui (Martinsson-Wallin 2000). Other early features found during excavations of *ahu* structures, as has been indicated by Ayres et al. (2019), are refuse pits found at Vinapu, Akivi, Tahai, and Heki'i. At Heki'i several pits were found during excavations on the west side, outside the courtyard pavement (Martinsson-Wallin 1998), and one was dated by a burnt palm nutshell to AD 1280–1396 (Cal. 2σ) (Ua-11701, BP 700 + −45).

Fire is another theme of early ritual behavior. One small fire pit found under the pavement stones at Heki'i gave a date on burnt palm nutshell to AD 1278–1396 (Cal. 2σ) (Ua-11700, BP 705 + −45). Another fire pit found behind a smaller attached *ahu* just west of Heki'i gave a date from a level under the rear wall to AD 1185–1384 (Cal. 2σ) (Ua-11704, BP 795 + −50). At *ahu* Ra′ai, small fires and sooty layers have been found inside and under the *ahu* as well as under the ramp, and they were all dated to AD 1294–1456 (Cal. 2σ) (Wallin and Martinsson-Wallin 2008: 148–149). Charcoal fragments were also found under pavements and ramp features at *ahu* Ura Uranga te Mahina, which have been dated to the period of AD 1300–1425 (Ayres et al. 2019: 280–281). These activities are often found in association with sites that later on developed into *ahu* structures and were rebuilt and used for a long period of time. We suggest that uprights, refuse and fires, are phenomenon seen all around Rapa Nui prior to, or in connection with, initial *ahu* construction.

Such early ritual features found on Rapa Nui can be compared to similar features found in East Polynesia dated to the same time period. For example at the Ha'atuatua site on Nuku Hiva in the Marquesas Islands, an upright stone with human burials, a fire pit, and a rectangular pavement have been dated to c. AD 1200–1400 (Rolett and Conté 1995: 224–225; Suggs 1961: 63). On Huahine, in the Society Islands at the early Vaito'otia/Fa'ahia site, there was a single stone upright in association with what has been interpreted as storage houses dated to around AD 1100–1300 (Anderson and Sinoto 2002: 246). The overview map of that site indicates different activities in the area, such as residential areas, an elite meeting-house and a site with a stone upright and storage features (Sinoto 1988: 128). In Norfolk Island, there was a simple pavement with three small uprights as well as postholes dating to c. AD 1250–1450. It was located above and a little bit away from the ordinary habitation (Anderson and Green 2001: 48). In New Zealand, there were no *marae* stone structures, but instead stone uprights called *tuahu* and poles called *pouahu* and other fenced-in areas, wooden images, as well as pavements (Best 1924: 288). Small stone images are also mentioned in connection to sweet potato fields (Leach 1984: 72). The initial settlers of New Zealand came from Central Polynesia around AD 1200 (Wilmshurst et al. 2011: 1818) and brought such images and features to New Zealand (Leach 1984: 42–43). On Maupiti, in the Society Islands, an early burial ground was found on a small island called *Motu Paeao* (Emory and Sinoto 1964). On the site was a row of 10 upright stones. Anderson et al. (1999) re-investigated the site and developed a series of new ^{14}C dates, which placed the burial site at AD 1300–1450 (Anderson et al. 1999: 61).

Based on archaeological research, it is likely that Polynesian early ritual space contained stone uprights, poles, planks, images, fires, burials, feasting, refuse pits and storage features. The traditional *ahu/marae* structure made up of stones developed later but the early features were continuously incorporated into the *marae* structures/concepts, when they became monumental in Central East Polynesia around AD 1400 (Kahn 2016; Wallin and Solsvik 2010).

Based on previous research on early ritual spaces in East Polynesia, we suggest that they were special places that incorporated natural landscape features and culturally shaped features with ritual connotations that varied in shape and function. They all pre-date the initial phases of *ahu/marae* structures with monumental architecture, and the activities seen at Nau Nau East fit well into an early ritual framework and we interpret this activity area as an early ritual space at Anakena. Subsequently, the materialization of the *ahu/marae* made the ritualized sites institutionalized and the different actions were formalized, which made it possible for the high chiefs to control the rituals through specialized priests. At Anakena this happened around AD 1300–1400 when the first stone platform of *ahu* Nau Nau was built on top of the old settlement at the site.

Acknowledgements Our thanks go to our mentor and old friend, the late Professor Arne Skjølsvold, who asked us the question: “Do you two want to participate in the excavations in Easter Island”?. Our answer was obviously Yes! We also want to thank our friend the late Thor Heyerdahl, who accepted Arne’s question . . . -and later himself invited us to other excavations in Peru and Tenerife. In addition, we are grateful to the late Director of the Kon-Tiki Museum Knut Haugland who later gave us employment at the Museum. We are most grateful to Dr. (Hon.) Sonia Haoa Cardinali, without her friendship and collaboration we would not have been able to do archaeology on Rapa Nui. Last, but not least, we send a thought to our foreman at the Anakena excavations the late Sr. Juan Haoa and his Rapa Nui crew, whom were the real archaeologists in the field and gave us so many laughs and friendly hugs!

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Part II
The Ancient Rapanui Culture

Chapter 7
A Behavioral Assessment of Refuge Caves (*ana kionga*) on Rapa Nui

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1 Introduction

Caves were some of the first site types investigated in Rapa Nui since they contained artifact rich stratigraphic deposits that were potentially informative about diachronic trends in stone tool technologies and subsistence (Ayres 1975, 1979, 1985; Smith 1961). Archaeological survey in the southwestern part of Rapa Nui (McCoy 1976) documented four variants that included overhangs (*karava*), lava tubes or lava bubbles (*ana*), boulder enclosures within the Rano Kau crater, and laves tubes with tunnel entrances (*ana kionga*), the last of which are hypothesized to represent refuge caves used during periods of conflict (Métraux 1940). In a recent paper (Stevenson et al. 2019) on the excavation of an architecturally modified cave (Fig. 7.1, Site 6–357 show on map), it was proposed that refuge caves with tunnel entrances represented a prepared ritual space, hypothesized to have been used by contestants in the leadership competition for Birdman. Radiocarbon and obsidian hydration place the creation and use of the cave interior between AD 1700–AD 1875 with peak usage around AD1788. The near convergence of the beginning date with the date of island re-discovery by Europeans in AD 1722 suggests that architecturally modified caves with tunnel entrances may be a post-contact occurrence and indicative of a major perturbation in the ideological configuration of Rapanui society.

In many studies of prehistoric cultural change, evidence for a socially transformative period is reflected by a change in society's central institutions (Tainter

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_7

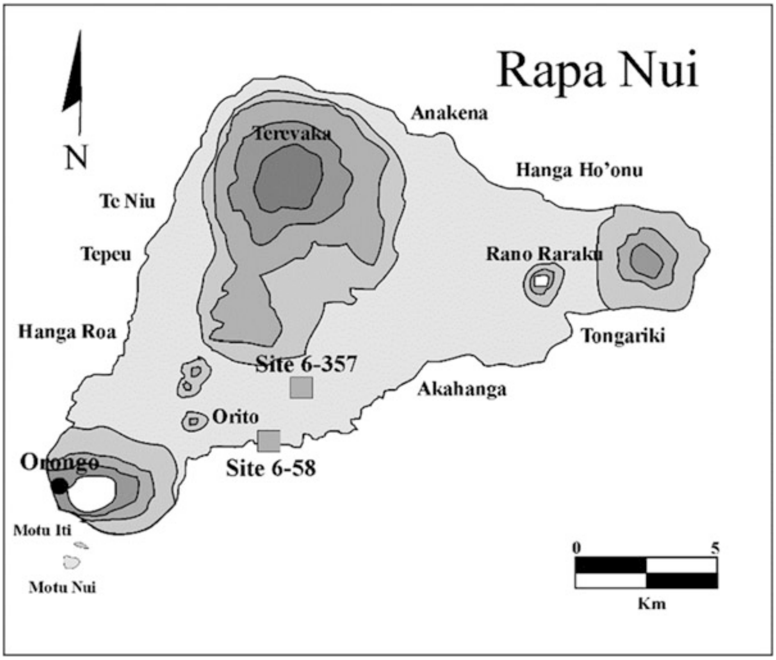

Fig. 7.1 Map of Rapa Nui with the location of Site 6–58, Site 6–357, ‘Orongo, and obsidian quarries

1988). On Rapa Nui one such occurrence is the emergence of the Birdman Cult which becomes the dominant spiritual focus that replaces the institution of ancestor worship (Routledge 1919). The timing for this transition is not firmly established, and various scholars have proposed that it was a secondary cult that paralleled the institution of ancestor worship for many centuries until the AD 1500s when it emerged as a dominant focus for unspecified reasons (Van Tilburg 1994; Lee 1992). This transformation was manifested by the construction of approximately 50 stone houses at the ritual center of ‘Orongo on the edge of the Rano Kau volcanic crater (Fig. 7.1).

More recently, other scholars have reevaluated the chronometric and stratigraphic evidence at ‘Orongo and hypothesized that the Birdman Cult had its roots in the traumatic impact of early European contact and the possible introduction of disease by Spanish navigators in AD 1770 (Hunt and Lipo 2011; Robinson and Stevenson 2017). There is clear evidence for an indigenous concern and even a preoccupation with western visitors. Ship petroglyphs appear superimposed on *moai* at the Rano Raraku statue quarry (SkjØldsvold 1961) and on walls within coastal caves (Lee 1992), paintings in the houses at ‘Orongo depict European ships (Ferdon 1961; Routledge 1920) and large earthworks (*miro o’one*) (McCoy 1976; Stevenson and Haoa 2008), and burial chambers (*ahu poepoe*) (Shaw 2000) appear in the form of European sailing vessels. Historic European artifacts clearly link these architectural features to the post-contact period. Routledge (1919) reports finding trade beads in an *ahu poepoe* and long strands of metal wire were found within the center of the *miro o'one* (Love, personal communication). Although the ceremony was not performed in the time that ethnologist Alfred Metraux was on the island, his informants were able to recall the chants that took place when persons converged at the "earth-ships" (Métraux 1940).

In this chapter, we again challenge the idea that architecturally modified caves are places of refuge and look for evidence that supports an alternate interpretation. We first consult the Pacific ethnographic database to examine "refuge caves" in other parts of East Polynesia, fully aware that the oral histories of the region may have been altered by traumatic contact period events and may not reflect the full diversity of cave uses. We then describe and chronologically date the stratigraphic deposits from an architecturally modified cave coastal cave (Site 6–58) on Rapa Nui. We revive the hypothesis that architecturally modified caves were underground ritual precincts integral to the annual Birdman Cult ritual and document the reconfiguration of a coastal cave from a repeatedly utilized fishing task site to that of an artificially enlarged and formalized chamber with restricted access that was possibly marked as sacred by petroglyphs of the Polynesian god *Makemake.* We then examine the cultural assemblage to determine the range of site activities and how they changed over time as the purpose of the cave was reconfigured by its occupants.

2 Archaeological Correlates of Refuge Caves

The widely held supposition that warfare was frequent in Polynesian societies may be true for large islands such as Hawaii and New Zealand. However, it might be the case that some small island societies adjusted to the peculiar demands of life within a highly constrained ecological context by rejecting for the most part political infighting and conflict. These small societies developed from the same Ancestral Polynesian Society as large island societies (Kirch 2017) but adapted differently to the limited environments in which they found themselves. On Rapa Nui, it has been recently argued that a spatially dispersed population adopted a strategy of resource sharing rather than competitive warfare to counteract climatic unpredictability and the uneven distribution of resources (Hunt and Lipo 2018). The lack of other landscape features that reflect a defensive posture such as defended nucleated settlements, or hilltop forts, is not present on Rapa Nui and thus supports this interpretation. However, island size is not a strong predictor variable for conflict if we include the smaller island of Mangaia where warfare was a frequent approach to the resolution of political issues, as well as the small island of Rapa Iti where hilltop forts were numerous (Anderson and Kennett 2012; Ferdon 1965; Mulloy 1965).

Nevertheless, organized conflict occurred repeatedly in many Polynesian societies and refuge was a concept linked with warfare. Caves serving as places of refuge are noted in Hawaii (Bollt 2005; Kennedy and Brady 1997), Mangaia (Walter and Reilly 2010), Mangareva (Laval 1938), Santa Cruz and Reef Islands (O'Farrall 1904), and Samoa (Freeman 1943, 1944; Nelson 1925; Ward and Moyle 1981). Case examples from Samoa, where there is an ethnographic oral history associated with refuge caves, are briefly described here to highlight some of the defining attributes for refuge enclosures and to demonstrate how they are architecturally different in comparison to architecturally modified caves (AMC) found on Rapa Nui.

2.1 Samoa

In an overview of cave types on Samoa, Roger Green (1969) identifies three forms of lava tubes that were used as water sources, religious sanctuaries, or places of refuge. Historical traditions (unspecified) and evidence for human habitation are the basis for his interpretation that some caves were refuge locations. The Faia'ai Cave on the island of Upolu, mapped by Green, is located of a rubble strewn slope. Piled boulders form a narrow opening that was previously covered by a stone slab resting nearby. The accessible portion is 428 feet in length, and the chamber contains 13 low platforms defined by stone perimeters and smaller stone infill. A rock pathway is present in the central portion of the cave, all of which is in total darkness. A small scoop well water source is about 25 feet in from the entrance.

Green (1969) also notes the prior work of Freeman (1943, 1944) in the investigation of Seuao and Falemaunga caves. The Seuao lave tube is located about three miles from the existing village of Sa'anapu. It is historically associated with refuge based upon the oral history of a land boundary dispute between the Tuamasaga and Atua groups that broke out 19 generations ago (Kraemer 1902). Out-matched in the confrontation, the Tuamasaga warriors along with men, women, and children retreated into this cave. This narrow-entranced cave with an opening of 3.6 x 4.0 feet opened up into a uniform chamber that covered 1866 feet in length and averaged 25 feet in width and 12 feet in height. A length of 750 feet was continuously modified by stone platforms on either side of a central stone pathway. Numerous earth ovens, surface hearths, and ash deposits were identified as was pig bone, pig teeth, shell, and five adzes. The duration of the refuge period is unknown, but the Atua eventually discovered the cave and were about to smoke out the inhabitants with fire when a ransom was paid and a crisis averted.

At Falemaunga Cave (Freeman 1944), the oral history is a little less specific, but it associates the cave with a refuge space for woman and children during Togan invasions of the past. The cave is located in the central region of Upolu and about 5.5 miles from the north coast and the village of Malie. The lave tube shares many architectural features with Seuao Cave such as the restricted entrance and many (n = 152) stone platforms. Evidence of cooking in the form of earth ovens and hearths was abundant as were pig bone and shell recovered from deep ash deposits. The ash deposits contained multiple wood types which may have provided light by torch or coconut oil lamps in the dark interior.

A lava tube refuge cave situated near the village of Tufutafo'e (location not released) on the north coast of the island of Savai'i in Western Samoa was reported by Ward and Moyle (1981) from their 1968–69 fieldwork. No local knowledge of the cave nor any legends about the site were obtained and thus the interpretation here is an archaeological one. The entrance to the lava tube refuge cave was visible to approaching outsiders. The lava tube interior was large and the roof height ranged between 12 m at the entrance and to little more than one meter at its furthest negotiable extremity. The tube width varied correspondingly from 15 m to less than 2 m. The cave depth reached a maximum of 550 m.

Upon entering, the tunnel was restricted by a small wall of about 0.5 meters in height which limited the passage to a crawl space. At about 30 m further into the cave, and immediately below a small opening in the roof, were four stone platforms. The interior of the cave had further walling and other features such as hearths and middens. At about 250 m from the entrance was an area littered with animal bone and the shells of marine species. Two large walls of stone taken from the tube insides had been built within 20 m of each other to block off sections of the cave. These blocked-off sections were characterized by their prepared surfaces. Within the cave, platforms of considerable size were on the cavern floor and floor was also paved. Deeper into the tube, the floor sloped sharply downward. Here, a stone mortar and pestle were found. Ten meters further on was a large stone pounder, together with quantities of mollusk remains, a wooden spearhead, and a human cranium. A total of seven stone adzes were found, along with various fragments and flaking debris. The entire cave lacked any evidence of petroglyphs or rock art. However, pigments of red and brown ochre were found within the cave. Activity in this cave was restricted to the dark zones. The cave location provided access to freshwater nearby and food provided by reef flats and outside gardens.

3 Rapa Nui Cases

In this study, we cautiously use cross-cultural analogy in identifying the basic features of refuge caves acknowledging the fact that the use and meaning of places on the landscape may have rapidly changed during early European contact (White 2018). Based upon our small sample, the term refuge cave indicates a lava tube that can be (1) geographically isolated, (2) spatially large, (3) contains evidence of domestic occupation in the form of cooking/heating/lighting (earth ovens and hearths) and food consumption, (4) has internal structural modifications to increase defensive capability, (5) possesses large numbers of platforms that served as sitting/sleeping areas, and (6) has a particularly difficult-to-access entrance.

In juxtaposition to this, the surveyed refuge caves on Rapa Nui (Stevenson and Haoa 2008; Stevenson et al. 2019) are small in size with low ceilings, nearly completely dark, and without hearths or earth ovens, lack internal walled subdivisions, and have man-made tunnel entrances of easily recognizable shaped stone, and occur frequently within the domestic settlement pattern on the coastal zone. These contrasts suggest that refuge was an unlikely function for architecturally modified caves (AMC) known conventionally in the Rapanui language as *ana kionga*.

Further evidence for the interpretation that AMC are ritual spaces rather than refugia comes from the excavation of Site 6–357 located on the southern coastal plain of Rapa Nui (Stevenson et al. 2019). In addition to the formalized entrance tunnel, the cave interior provides evidence of elaborate preparation. The small natural lava tube was expanded through excavation to an 8 m x 4 m x 1 m interior, and the tailings were placed outside on top of the surface basalt outcrop. The base of the cave was made flat and an imported white clay was heated to 600 °C to eliminate moisture and a 1-2 cm thick floor was installed (Stevenson et al. 2019). A small side chamber and stone platform of worked blocks were added to complete the interior space.

A cross section of a floor sample demonstrated that six identifiable 2–3 mm reapplications of white clay occurred during the use life of the cave; a stratigraphic structure which suggested the refurbishment may have been linked to a recurring event. Cultural artifacts imported into the cave consisted of sewing needles and obsidian tools which through high-power use-wear analysis demonstrated they were used in processing green plants and the working of bone and wood (Church and Ellis 1996). Distributions of red and black pigments were also present on the floor along with high concentrations of faunal remains of fish, chicken (*Gallus gallus*), and to a lesser degree, rat (*Rattus exulans*) (Rorrer 1998) and small shells (Rorrer 1997). Taken as an associated assemblage, the behaviors that may have created these remains could have entailed intensive costume preparation, body decoration, and food consumption over a short time interval of a few days or weeks. Radiocarbon and obsidian hydration dating places these activities as occurring just before and within the post-European contact period (AD1700–1875).

Site 6–58 is architecturally similar to the AMC of Site 6–357 described above. We approach the analysis of Site 6–58 with the goal of testing the hypothesis that the AMC is an intentionally prepared place for a recurring ritual that was conducted after European contact. We will look at the site formation processes, the site architectural structure, and the cultural assemblage to determine how the activities within the AMC are different from activities within the coastal cave prior to its architectural transformation.

4 Site 6–58: A Coastal Cave

Site 6–58 is a sub-rectangular cave located on the southern coast of Rapa Nui (Fig. 7.1). The entrance to the cave is located on the eroded basalt shoreline, approximately 20 m above the ocean. The interior dimensions of the cave measured 13 m in length and almost 7 m at the widest point (Fig. 7.2). At the entrance of the cave the ceiling was over two meters from the current floor level. The height of the cave ceiling declined toward the central section where it was approximately a

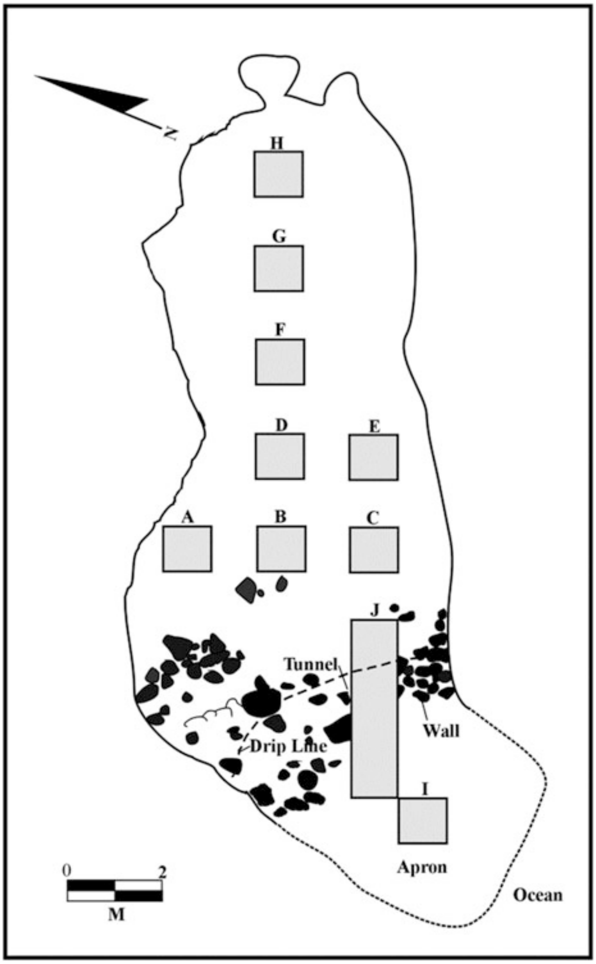

Fig. 7.2 Top plan of Site 6–58 with test unit locations

meter in height, before it again opened up toward the rear and rose to a height of approximately 2 m.

The current surface is higher than the last cultural occupation level. The floor of the cave was uniformly covered by a fine medium brown sediment that had washed into the cave by above-ground surface run-off. The cave is still frequently flooded during the rainy season, and as we witnessed, the heaviest flow of sediment and water entered the cave on the northern side of the entrance. This influx of soil deposits has served to seal the underlying historic and prehistoric occupation levels. The entrance to the cave was also defined by the presence of a collapsed and disarticulated wall placed across the opening. On the exterior side of the wall was a heavily eroded but level area, or apron, that extended to the edge of the sea cliff.

4.1 Stratigraphic Summary

We offer a summary and interpretation of the cave stratigraphy and architecture as seen in the east-west test unit soil profiles (Fig. 7.3). Five strata were present within the unit. At the top, Level 1 consisted of a medium brown alluvium without cultural material. It was 40–60 cm thick and contained micro-strata of individual flooding events. This was underlain by a darker loam soil (Level 2) cultural level containing obsidian and faunal material. Preserved under this deposit was a white clay floor (Level 3) that rested upon a few centimeters of earlier deposits rich in faunal elements (Level 4). A natural deposit of non-cultural red scoria (Level 5) was then encountered.

In the lowest level, a high amount of faunal refuse was encountered. This level preserved under the white clay floor lacked internal stratigraphy and reflects the long-term use of the cave during exploitation of the coastline. It was possible that the occupants were primarily fishermen who utilized the cave for short periods between fishing episodes. A small stone platform was in the central portion of the cave and partly imbedded into this level. It may have been used in daily activities or sleeping.

Later in time the cave was extensively modified. A front entrance wall with a tunnel entrance was added, and a prepared floor of white clay was placed in the front two-thirds of the cave. These attributes indicate that the cave was transformed into restricted space with limited access. At this time, it is proposed the rear portions of the cave were also enlarged. However, no direct evidence is available to support the assertion other than that it is consistent with the effort associated with the preparation of the clay floor and construction of the front wall. The cave was refurbished at least once by the addition of new white clay flooring material.

The use of the cave as a restricted space lasted for an indeterminate amount of time. At some point, the entrance wall collapsed and the drainage pattern changed so that water run-off entered the cave from the northern side of the entrance. From this point on, sedimentation was frequent, and the low density of cultural material suggests that the cave was never used on a regular basis.

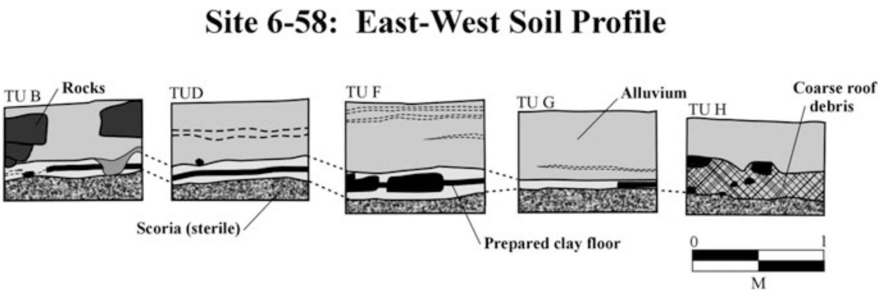

Fig. 7.3 Site 6–58 East-west soil profile. Distances between test units are 1 m but shortened here to fit to the page; thus, elevation differences are exaggerated

Table 7.1 Archaeological excavation levels by phase at Site 6–58

Test unit	Phase 4 Alluvium	Phase 3 Floor surface	Phase 2 Clay floor	Phase 1 Subfloor deposits
A	1–4	5	6	7–8
B	1–3	4	5	6
C (omit)	1–2	3	4	5
D	1–7	8	9	10
E	1–4	5–6	7	8–10
F	1–3	4–5	Trace presence	6–8
G	1–2	3	4	5–6
H	Unknown	Unknown	Unknown	Unknown
I	Unknown	Unknown	Unknown	Unknown
J	Unknown	Unknown	Unknown	Unknown

We have been able to partition the stratigraphy into four distinct contexts (Table 7.1) that because of their superposition will be time sensitive. The deepest deposits located below the clay floor reflect the initial use of the cave. These soils are referred to as the Phase 1 occupation. Phase 2 is a short-term event that consists of the installation of the white clay floor. Phase 3 is represented by the soils and cultural material 1-2 cm immediately above the clay floor. Lastly, Phase 4 consists of the periodic flooding of the cave and accumulation of surface sediments. We have assigned our excavation levels to each of these phases for Test Units A–G. Phase-specific deposits for Test Unit H deep inside the case or for Test Unit I on the cave apron cannot be assigned a phase identification since the stratigraphy cannot be linked to the central part of the cave. The front wall that sealed the cave opening, and exposed by Test Unit J, was part of the Phase 2 construction.

5 The Chronology of Site 6–58

5.1 *Radiocarbon Dating*

AMS dating was conducted on carbonized material from cultural deposits below and above the white clay floor with the goal of defining the length of cave occupation and the time period for the installation and use of the clay floor. Five samples from short-lived plants consisting of small woody twigs and grass were selected for analysis because of their limited growth. They were not identified as to plant species (Table 7.2). The samples were radiocarbon dated by Beta Analytic of Coral Gables, Florida. The uncalibrated dates were corrected to 2-Sigma date ranges using the southern hemisphere calibration in Calib 8.1 (Stuiver and Reimer 2016).

The AMS results indicate that Site 6–58 was occupied from the early seventeenth century to the twentieth century. The multiple intercepts on the calibration curve make it difficult to determine time differences for contexts below and above the

Table 7.2 AMS dates from cultural layers at Site 6–58, Rapa Nui

Provenience	Context	Material	Beta no.	Uncal. date	Cal date 2-Sigma	Probability
TU E, L.5	Above floor	Charcoal	333,736	90+/−30	1698–1724	0.1079
	(phase 3)	(grass)			1808–1839	0.2531
					1842–1869	0.0929
					1876–1948	0.4961
TU E, L.6	Above floor	Charcoal	339,383	200+/−30	1654–1712	0.2478
	(phase 3)	(twig)			1718–1813	0.5391
					1835–1890	0.1346
TU F, L.5	Above floor	Charcoal	333,737	110+/−30	1697–1725	0.1397
	(phase 3)	(grass)			1807–1873	0.3666
					1875–1953	0.4937
TU F, L.8	Below floor	Charcoal	339,384	260+/−30	1629–1681	0.4730
	(phase 1)	(grass stem?)			1730–1802	0.5269
TU D, L.10	Below floor	Charcoal	333,735	100+/−30	1697–1725	0.1245
	(phase 1)	(grass)			1807–1870	0.3574
					1875–1954	0.5181

white clay floor and the probabilities associated with the age ranges are conflicting. The sample from below the floor in TU F, L. 8 (Beta 339,384) dates to AD 1629 to AD 1802, while a charcoal fragment from the same subfloor zone in TU D, L.10 (Beta 333,735) has an 87% probability of occurring after AD 1807. Above the floor the situation is not any clearer. The charcoal from TU E, L. 5 has the highest probability of occurrence after AD 1805 (Beta 333,736) as does the specimen from TU F, L.5 (Beta 333,737), but a third sample from the same context (Beta 339,383) has a 77% probability of occurring before AD 1813.

If the individual probability sets are summed for all the AMS dates, the temporal activity at the site is slightly better defined (Fig. 7.4), with a lower probability of site usage occurring from AD 1640–1730 and more sustained activity from AD 1810–1920 (Fig. 7.4).

5.2 Obsidian Hydration Dating

Obsidian hydration dating was used to date the stratigraphic deposits because of its ability to produce age estimates for the last three hundred years. A suite of 25 obsidian flakes was selected from the assemblage contained within Test Unit F since the stratigraphy above and below the white clay floor was well defined in this excavation unit (Fig. 7.3). Transparent geological thin sections were prepared, and hydration layer thickness was measured with an Aus Jena polarizing light microscope coupled to an image-splitting micrometer. Several independent readings were averaged, and the measurement precision for the samples was 0.08–0.10

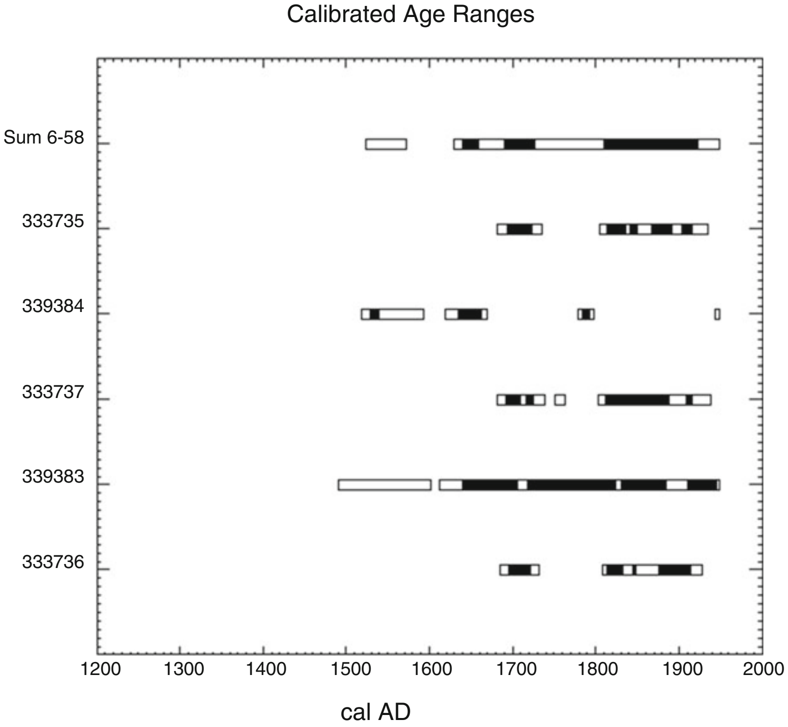

Fig. 7.4 Probability distributions for AMS dates from Site 6–58, Rapa Nui

micrometers. The optical hydration layers ranged in thickness from 0.87 to 1.94 micrometers (Table 7.3).

An obsidian hydration rate at 160 °C and the activation energy have been developed in the laboratory for the Orito obsidian source under conditions of 100% relative humidity (Stevenson et al. 2019). An archaeological hydration rate is extrapolated from the high temperature laboratory developed water diffusion coefficient using the Arrhenius equation:

$$K = A\ \exp{-E_a/RT} \tag{7.1}$$

where K is the archaeological hydration rate in micrometers^2/year at ambient temperature; A is a high temperature diffusion coefficient (1.44 um^2/day at 160 °C); E_a is the activation energy (86,401) in Joules/mol for the diffusion process; R is the universal gas constant (8.314 Joules/mol); and T is archaeological temperature in degrees Kelvin (292.95 K or 19.8 °C). With these constants, the high temperature hydration rate may be extrapolated to known ambient conditions at the archaeological site.

Table 7.3 Obsidian hydration dates by level for Site 6–58

Lab No.	Test Unit	Level	Context	Width (um)	Date AD	S.D.
92–637	F	5	Floor surface	1.13	1754	43
92–638	F	5	Floor surface	0.87	1849	34
92–639	F	5	Floor surface	0.97	1815	37
92–640	F	5	Floor surface	1.00	1804	39
92–641	F	5	Floor surface	1.01	1801	39
92–645	A, B	Floor	Floor	0.87	1849	34
92–644	A	Floor	Floor	1.03	1793	40
92–643	B	Floor	Floor	0.93	1829	36
92–630	F	6	Subfloor	0.96	1819	37
92–631	F	6	Subfloor	1.03	1793	40
92–632	F	6	Subfloor	1.16	1741	44
92–633	F	6	Subfloor	0.96	1819	37
92–634	F	6	Subfloor	0.96	1819	37
92–635	F	6	Subfloor	0.96	1819	37
92–624	F	7	Subfloor	1.26	1696	48
92–625	F	7	Subfloor	1.23	1710	47
92–626	F	7	Subfloor	1.04	1789	40
92–627	F	7	Subfloor	1.07	1778	41
92–628	F	7	Subfloor	0.87	1849	34
92–629	F	7	Subfloor	1.36	1648	52
92–618	F	8	Subfloor	1.94	1297	73
92–619	F	8	Subfloor	1.57	1535	60
92–620	F	8	Subfloor	1.44	1607	55
92–621	F	8	Subfloor	1.69	1463	64
92–622	F	8	Subfloor	1.86	1353	70

In 1988, soil temperature and relative humidity salt-based monitoring cells were planted within the central section of Site 6–58. A single cell pair was buried at a depth of 10 cm approximately 8 meters back from the cave opening. At this location no sunlight fell upon the cell location. At the end of one year, the cells were removed and an effective hydration temperature of 19.8 °C and a relative humidity of 100% were determined (Stevenson et al. 1993). The temperature adjustment to the pre-exponential resulted in a hydration rate of 5.41 um^2/1000 years which was used to convert the hydration rim widths into absolute ages.

X-ray fluorescence analysis was not conducted to determine the artifact geological source identification. In its place, glass density determination was conducted on each artifact to estimate the structural water content since this parameter is used to model the hydration rate (Stevenson and Novak 2011; Stevenson et al. 2021). Recent structural water content analysis of the artifacts from each of the four Rapa Nui geological outcrops (Orito, Motu Iti, Rano Kau I, Rano Kau II) has shown that the structural hydroxyl content for each source is 0.10% with a standard deviation of 0.005%, or less, for each source (Stevenson et al. 2018). Thus, all

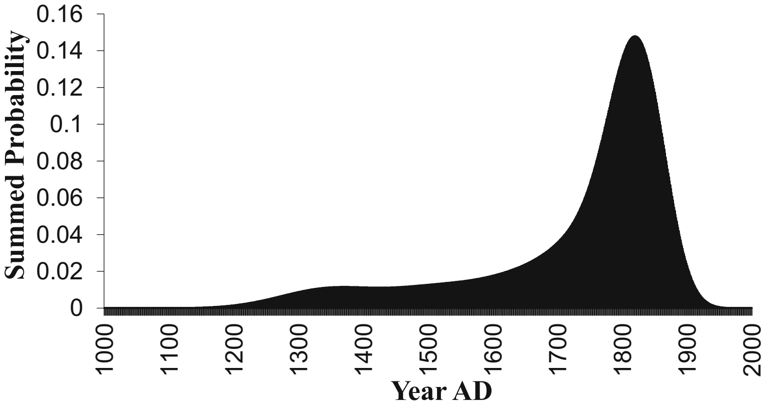

Fig. 7.5 A summed probability distribution of obsidian hydration dates for Site 6–58

Rapa Nui obsidian, regardless of source, will hydrate at the same rate at a specified temperature.

Obsidian artifacts from Test Unit F, Level 8, located below the floor produced the earliest dates which ranged between AD 1297 and AD 1607, a span of approximately 300 years (Table 7.3), Higher up in the soil profile, but still located below the floor, were obsidian samples from Levels 6 and 7. The dates ranged in these two levels ranged between AD 1648 and AD 1849. The dates from these two levels are all later than the dates from Level 8 and exhibit a time span of 201 years. Three samples (92–643, 92–644, 92–645) were found imbedded in the clay floor and provided dates (AD 1793–AD 1849) which closely match the age of the deposit (AD 1741–1819) immediately below the floor. The samples above the clay floor date to AD 1754 to AD 1849 with all but one of the five dates occurring in the nineteenth century. A summed probability distribution of the mean dates (Fig. 7.5) with one standard deviation places the peak usage of the cave in AD 1811. Occupation of the cave in the earliest period seems to have been intermittent over 300 years with little development of the soil profile. However, in the late seventeenth to early 19th century Levels 6 and 7 are formed. The clay floor is installed in the early nineteenth century and the cave visited for approximately 50 years afterward.

6 Analysis of Cultural Features

6.1 X-Ray Diffraction of the White Clay Floor

Compacted clay living floors in caves are rare on Rapa Nui and have not been recognized by other researchers in the previous excavations (Ayres 1975; Smith 1961) although a compressed living surface was identified within an upland field

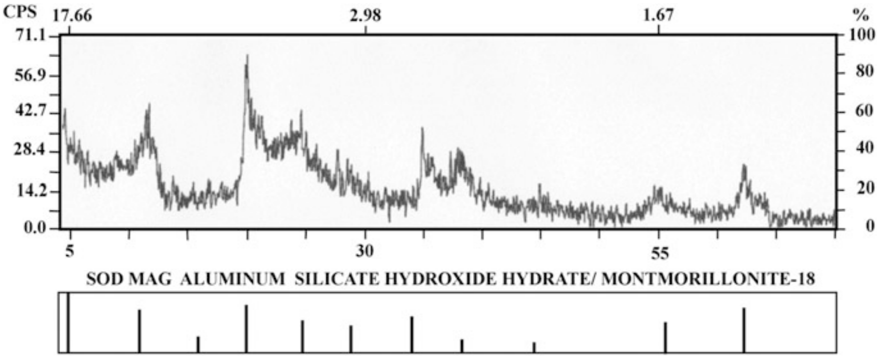

Fig. 7.6 An X-ray diffraction spectrum for the clay floor at Site 6–58 with the library search result and peak locations marked by vertical bars below

house (Stevenson et al. 2007). The occurrence of a distinctive white clay floor within Site 6–58 is identical to one discovered within AMC Site 6–357 located about a kilometer inland (Stevenson et al. 2019). White clay has also been found as a flooring of the ritual water basin at Ava Ranga Uka a Toroke Hau in the quebrada of Maunga Terevaka (see Mieth et al. this volume). As a first step in the identification of the material, we conducted X-ray diffraction (XRD) to establish its crystalline structure.

The sample was lightly ground in an agate mortar and pestle and air dried. Powder XRD was conducted using a Scintag diffractometer at the Pennsylvania State University. The sample was placed onto a zero-background holder, and a single scan was compiled which had a scanning step size of 0.03° with the 2θ values ranging from 4° to 70° (Fig. 7.6). Peak positions were compared against the mineral reference library, and montmorillonite clay was identified as the best match. White montmorillonite was the same material installed at Site 6–357 with the added condition that the clay had been heat treated prior to installation possibly with the intention to dry the moist clay. In the case of the clay flooring clay at Site 6–58, it was not thermally treated prior to installation (Stevenson et al. 2019).

The distribution of clay deposits on Rapa Nui has not been systematically researched although the contemporary Rapa Nui are known to frequent colored clay deposits in the vicinity of Ahu Vinapu on the west coast about three kilometers from Site 6–58. The white clay added to the cave deposits at Site 6–58 is likely a distant source and thus reflects a considerable investment of effort in the cave refurbishment process.

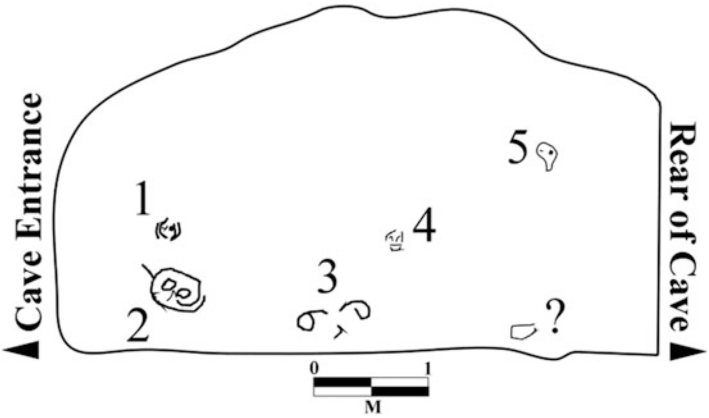

Fig. 7.7 *Makemake* petroglyphs identified on the north wall of Site 6–58

6.2 Petroglyphs

Along the northern wall of the cave within 5 m of the dripline, five petroglyphs were present (Fig. 7.7). All of the petroglyphs appear to have been representations of the deity *Makemake*. Each of the images were outlines of faces of various sizes and were formed by pecking of the cave wall in order to raise an image. In some instances, the pecked areas were often smoother than the surrounding wall matrix and served to define the perimeter of the face.

6.3 Lithic Reduction Analysis

Rapa Nui lithic technology consists of unifacial reduction which has a limited diversity of tool forms. Several researchers have studied either the general reduction sequence (Stevenson et al. 1984) or specific tool forms (Ayres et al. 2000; Bormida 1951; Heyerdahl 1961; Mulloy and Figueroa 1978). In this analysis, we focus on a general description of assemblage reduction followed by an analysis of individual tool types and a discussion of high-magnification use-wear completed on a sample of *matā* recovered from the cave (Kononenko et al. 2019).

Based upon an analysis of an assemblage from the Orito quarry the obsidian reduction sequence consisted of two general trajectories. Large thick tabular slabs of glass from the quarry are thought to have been preferentially selected for more massive block cores from which large flakes were produced. These large flakes were preferred for the manufacture of *matā* (Stevenson et al. 1984). It has also been noted that large flakes with two ventral surfaces (*kombewa* flakes) were sometimes produced (Bollt et al. 2006). Most of this primary reduction associated with *matā* manufacture is assumed to have taken place at the quarry given the labor costs of transporting large amounts of material off-site. It was also proposed that smaller pieces of tabular raw material were preferentially used to produce small discoidal cores which could then be easily transported to habitation areas removed from the quarry area (Stevenson et al. 1984). Thus, the lithic analysis at Site 6–58 was conducted to examine if the stages of the core reduction sequence were present and if these activities varied with the time of cave utilization.

The excavation and flotation process resulted in the recovery of 1554 obsidian flakes or flake fragments. The Phase 1 levels produced 1264 (81.3%) flakes or flake fragments, the Phase 2/3 levels 231 (14.9%), and the Phase 4 levels 59 (3.8%). The assemblage from each context was first sorted into primary, secondary, and tertiary flake groups. Primary flakes were defined as those having cortex over the entire ventral surface, while secondary flakes had a lesser amount of cortex due to previous flake removal. Tertiary flakes possessed no geological cortex. Each group was then sorted by size category (0–2.5 cm, 2.51–5.0 cm, >5 cm). Broken cortex and non-cortex flakes were sorted into the same size categories. Extensively retouched flakes and tools were removed from the assemblage at this point for a separate analysis.

The Phase 1 occupation at Site 6–58 produced 423 whole flakes and 841 flake fragments. Tertiary flakes and tertiary flake fragments predominated and account for 1065 items or 84.3% of the assemblage, while primary and secondary flakes constitute a minor component (Table 7.4). A large amount of the lithic debitage is fragmented, and this suggests that lithic reduction by percussion was conducted within the cave during the earliest occupation of the site prior to its transformation to an AMC. The largest numbers of flakes across all flake size categories are within the 0–2.5 cm range. This suggests that flakes of this size were the intended end-product of reduction activity conducted most frequently, but not exclusively, on prepared cores.

The Phase 2/3 levels produced 104 obsidian whole flakes and 127 flake fragments (Table 7.5). The quantity of discarded obsidian is substantially less than Phase 1, but the proportions of flakes by size and flake category are generally the same with small tertiary flakes dominating the assemblage. Distinct from the Phase I assemblage is the fact that large flakes, or flake fragments of 5 cm in size, are larger in number and proportionally greater. They constitute about 10% of the entire assemblage compared to 3% of the same size category for Phase 1. During each of these occupational periods, large flakes may have been produced elsewhere and brought to the site.

Table 7.4 Phase 1 flake types by size range

Flake size	Primary	Secondary	Tertiary	Primary and secondary fragments	Tertiary fragments	Size category Totals
0–2.5 cm	1	25	255	70	616	967
2.51–5.0 cm	3	31	93	45	83	255
>5.0 cm	4	6	5	14	13	42
Totals	8	62	353	129	712	**1264**

Table 7.5 Phase 2/3 flake types by size range

Flake size	Primary	Secondary	Tertiary	Primary and secondary fragments	Tertiary fragments	Size category Totals
0–2.5 cm	1	6	40	14	65	126
2.51–5.0 cm	1	20	24	19	20	84
>5.0 cm	0	5	7	6	3	21
Totals	2	31	71	39	88	**231**

Table 7.6 Phase 4 flake types by size range

Flake size	Primary	Secondary	Tertiary	Primary and secondary fragments	Tertiary fragments	Size category Totals
0–2.5 cm	0	0	11	2	12	25
2.51–5.0 cm	1	7	5	6	6	25
>5.0 cm	0	0	2	6	1	9
Totals	1	7	18	14	19	**59**

During the Phase 4 use of the cave, only a small amount of obsidian debitage (n = 59) was deposited within the thick alluvium (Table 7.6). As a result, this small sample size does not provide an interpretable distribution of flake categories sorted by size.

It is useful at this point to compare these materials with the assemblage from Site 6–58 and elsewhere. Previous work by Stevenson et al. (1984) has presented flake type frequencies by size category for a habitation site at Akahanga village and the Orito obsidian quarry. At Akahanga, primary and secondary flakes constitute only 15% of the entire assemblage and are less than 5 cm in size. Tertiary flakes predominate (85%) and are also generally less than 5 cm in size. This pattern argues for the fact that prepared cores or flake blanks are being transported to the site for smaller flake production or the manufacture of smaller flake tools. In contrast, at the Orito quarry primary and secondary flakes are numerically dominant and make up 85% of the sample. Here, tertiary flakes are rarely greater than 5 cm, but larger primary and secondary flakes in the >5 cm category are frequent. This pattern argues for initial decortication activity, core trimming, and *matā* manufacture. Site 6–58 is within 2 kilometers of the Orito quarry, but the flake sizes are smaller and more aligned with the Akahanga sample.

In summary, the Phase 1 occupation levels produced the highest quantities of obsidian flakes which most likely reflects its extended occupational history of approximately 300 years. The flake category size distributions show the assemblage to be closest to the Akahanga habitation pattern. Core preparation activities are minimal, and tertiary flakes dominate the assemblage. The Phase 2/3 assemblage is similar to that of the Phase 1 levels except that larger primary flakes are slightly more numerous and accumulated in a much shorter time period. This may reflect an emphasis on cutting/scraping activities that occurred in Phase 2/3. A few core fragments present in the cave within Phases 1 and 2/3 suggest that some lithic reduction was conducted on site and may have been responsible for the creation of much of the angular debitage.

7 Obsidian Tools

Macroscopic edge damage within the obsidian flake assemblage was very minimal, and only a few flakes or flake fragments with utilized or retouched edges could be identified. The most frequently occurring modified tool was an obsidian flake graver that was defined by slight retouching to create a sharp and pointed protrusion useful in scoring other materials. Seven gravers were within Phase 1 deposits and two others were found above the white clay floor in Phase 2/3 (Table 7.7). The other recognized tool was a flake scraper identified by micro-scarring along one edge. Three were present in Phase 1 and two in Phase 2/3. Other shaped tools such as spokeshaves, drills, and chisels found at other sites (Ayres 1975; Ayres et al. 2000) were absent. The noticeable absence of these shaped implement forms suggests that a more limited range of tasks were preformed in both the AMC and the deposits immediately below it. However, the lack of utilized flakes or flake fragments may be a problem of archaeological visibility and the macro-inspection of obsidian surface by eye. This may be especially problematic for situations where tools were used for short periods of time and then discarded without much physical damage imparted to the surface.

7.1 High-Magnification Use-Wear of Matā

Sixteen complete *matā* (Table 7.8) and 17 partial *matā* were recovered. Eleven complete *matā* were from Phase 1, three were from Phase 2/3, and two could not be assigned. Understanding the use of these tools has been a recurrent focus of archaeological studies on Rapa Nui, and the emerging consensus is that the vast majority of *matā* represent multi-purpose tools used in daily activities such as cutting plants (Church and Rigney 1994; Church and Ellis 1996; Church 1998), cultivation (Lipo et al. 2016), or possibly the chopping of soft wood during forest clearance (Stevenson and Williams 2018). In addition, observations by early navigators such as Captain Cook in 1774 noted that obsidian was hafted to wooden shafts that could have functioned as weapons.

As part of this study, Kononenko et al. (2019) conducted a use-wear analysis on a sample of *matā* from Site 6–58. Within Phase 1 deposits located below the floor, ten complete *matā*, 1 body fragment, and one kombewa flake (*matā* blank) showed evidence of use-wear. The most frequent activity (n = 4) was the margin-sawing/whittling/scraping of resinous or siliceous woody plant material. This was followed by the sawing/whittling/scraping of shell/bone (n = 3). Less frequently

Table 7.7 Obsidian and bone tool forms found at Site 6–58 by archaeological phase and test unit and level

Phase	Matā	Matā stem/blade	Graver	Flake scrape	Core frag.	Bone needles	Fish-hooks	Other tools
Phase 4 Total = 2	0	(B3) 1	B3 (1)	0	0	0	0	0
Phase 2/3 Total = 20	A5 (1) F5 (2)	(A3) 1 (D8)1 (E6) 1 (G3) 2	D8 (2) F5 (1)	(E4) 1 (F5) 1	(A5) 1 (E4) 1 (E6) 1	A5 (2)	0	(E6) *Poro* tool, Scraper (G3) basalt grinder
Phase I Total = 56	A7 (2) D10 (3) E8 (1) E9 (1) F6 (1) F7 (1) F8 (1)	(A7) 2 (B6) 2 (E8) 1 (E9) 1 (F6) 4 (G5) 1	A7 (2) B6 (2) E9 (1) F6 (1) G5 (1)	(A7) 2 (D10) 1	(F6) 2	A7 (3) A8 (1) B6 (2) D10 (2) E9 (1) F6 (2) F8 (7)	D10 (2)	(E8) Basalt pick (F7) Retouched basalt frag. (F8) *Poro* tool

Table 7.8 Attributes of complete *matā* from Site 6–58

Test unit	Level	Phase	Max. length	Max. width	Tang length	Mass (g)	Cortex on blade	Cortex on tang
A	5	2/3	80.58	77.31	27.93	69.80	No	Yes
A	7	1	62.99	39.33	18.43	21.20	Yes	No
A	7	1	62.79	51.17	22.15	27.50	Yes	No
D	10	1	73.01	39.70	23.37	28.10	Yes	No
D	10	1	74.66	41.86	23.58	28.20	Yes	No
D	10	1	65.76	62.56	23.39	42.00	No	No
E	8	1	57.10	38.51	20.59	11.80	No	No
E	9	1	62.15	49.31	15.92	29.10	No	No
F	5	2/3	70.76	58.88	25.24	44.50	No	No
F	5	2/3	83.24	74.08	23.61	62.10	No	No
F	6	1	63.5	38.15	21.45	21.60	No	No
F	6	1	70.30	60.54	25.85	40.0	Yes	No
F	7	1	64.17	72.21	33.36	31.80	No	No
F	8	1	61.72	61.39	20.26	35.50	No	No
I	2	?	52.75	41.41?	18.46	16.60	No	No
J	4	?	58.43	39.40	16.74	21.10	No	No

observed were two *matā* involved in the gutting of fish and one *matā* used to process soft plants/tubers. Above the floor in the Phase 2/3 deposits five *matā/matā* body specimens were analyzed along with three flakes. The working of woody plant material was the most frequent (n = 3) activity followed by the modification of siliceous woody plants (n = 2). The cutting/slicing of soft plants/tubers was identified on two tools and one flake showed no evidence of use-wear.

A comparison of the Phase 1 and Phase 2 contexts shows that the working of woody materials is the main activity in both cases, and in the Phase 1 levels, this is complemented by the working of bone/shell, plants/tubers, and the gutting of fish. In Phase 2/3, the use of *matā* for sawing/whittling/scraping of shell/bone was not identified nor was the gutting of fish. This suggests that fishing was less frequently conducted by occupants of the AMC. Nor were the bone or shell tools made for this activity.

8 Bone Tools

8.1 Needles

Bone on Rapa Nui was modified to form a variety of tools that included awls, tattoo combs, fishhooks, harpoons, and needles (Ayres 1975; Métraux 1940; Steadman et al. 1994). These forms are primarily preserved in caves, or beach dune contexts, where groundwaters are reduced, and preservation has been enhanced. A

Table 7.9 Bone needle attributes from Site 6–58

Unit	Level	Phase	Condition	Length	Width	Thickness	Eye diameter	Bone type	Eye type	Needle part
A	5	2/3	Whole	45.93	3.94	1.51	0.98	Human	Bi	–
A	5	2/3	Whole	53.52	3.48	1.28	1.12	Human	Bi	–
A	7	1	Whole	62.19	1.96	1.92	–	Fish	–	–
A	7	1	Broken	29.91	2.06	1.01	–	Human	–	Tip
A	7	1	Whole	71.09	2.64	1.77	1.11	Fish	Uni	–
A	8	1	Broken	26.38	4.08	1.37	1.06	Chicken	Bi	Base
B	6	1	Broken	45.10	3.72	1.43	–	Human	–	Tip
B	6	1	Broken	31.18	3.60	1.77	0.89	Human	Bi	Base
D	10	1	Broken	11.37	1.75	0.95	–	Chicken	–	Tip
D	10	1	Broken	13.79	2.77	1.29	–	Human	–	Tip
E	9	1	Whole	21.26	3.61	1.03	1.26	Chicken	Bi	–
F	6	1	Whole	46.21	3.95	1.58	1.23	Human	Bi	–
F	6	1	Broken	28.13	3.94	1.25	–	Human	–	Base
F	8	1	Broken	21.27	4.02	1.86	1.11	Human	Bi	Base
F	8	1	Whole	46.37	2.44	1.68	1.10	Chicken	Bi	–
F	8	1	Broken	42.26	2.96	1.35	–	Human	–	Tip
F	8	1	Broken	35.91	3.02	1.65	–	Human	–	Base

previous study of bone needle manufacture (Beardsley 1996) from the coastal caves excavated by Ayres (1975) observed that the needles in that assemblage were made from the femurs and tibia of chickens and other unidentifiable long bones. Needles were manufactured by splitting the long bone to create a concave bone blank. This was followed by grinding the blank to fashion and tip and basal element. The base was then unidirectionally drilled to form a hole for a thread approximately 1 mm in diameter. With extended use for sowing, the needle became polished and the tip rounded from soft abrasion. In some instances, a shallow groove was worn into the needle eye showing the direction in which the thread was pulled.

At Site 6–58, seventeen needles were recovered with 16 coming from Phase 1 deposits and two from Phase 2/3 contexts (Table 7.9). Whole and broken needles were represented and consisted of both tips and basal portions. In contrast to the sites analyzed by Beardsley (1996), only four needles were made from chicken bone. The majority of needles ($n = 11$) were fashioned from human bone, recognizable by its flat cross section, whiter color, and harder consistency. Two fish bone needles were also present. On 8 of the 9 basal elements, the concave depressions on each side indicated that the eyes were created by bidirectional drilling. It is possible that bone needles were used to sow tapa cloth for clothing or for the manufacturing of fish netting (Métraux 1940).

Table 7.10 Fishhooks from Site 6–58

Unit	Level	Phase	Condition	Shaft length	Point length	Point-shank width	Shaft diameter	Bone type
D	10	1	Whole	9.23	8.03	5.62	2.15	Chicken?
D	10	1	Partial	56.46	22.63	17.87	5.26	Human

8.2 Fishhooks

On Rapa Nui historic ethnographic observations document the presence of stone and bone fishhooks. Stone fishhooks were chipped, pecked, and ground out of a fine-grained basalt and are reported to have been used to catch larger fish such as tuna. Bone fishhooks are much more frequent. They are normally v-shaped, barbless, and with a carved projection at the point of the snood (line attachment). Composite fishhooks where the shank and point are lashed together have also been found archaeologically. Human bone as the preferred material for both types (Métraux 1940).

At Site 6–58 only two fishhooks were found in Phase 1 contexts located below the clay floor (Table 7.10). The smaller single-piece hook with a shaft length of nearly 10 mm was likely made from chicken bone, while the much larger hook with a shaft length of 56.46 mm was fashioned from human bone. No debris from fishhook manufacturing was identified in the analysis of the faunal material.

9 Faunal Remains at Site 6–58

The total number of faunal elements recovered by water flotation from Site 6–58 was 22,934. Due to the large size and time constraints, the assemblage was partitioned into the categories of fish, chicken/bird, rat, and mammal for each recognizable archaeological phase. Small shells were also part of the assemblage but were not included in this comparative exercise.

Fish remains made up the majority of faunal remains by both weight and number of identified specimens (NISP). Approximately 18,312 (79.8%) fish elements were recovered (Table 7.11). Fish remains appear to be evenly distributed throughout the site with numbers dwindling toward the back of the cave.

Bird remains were the second largest category and constituted 11.8% of the NISP. The vast majority of these bones likely belong to the Polynesian chicken although other marine birds may be represented. The distribution of bird remains, like that of fish, decline toward the rear of the cave.

Two other types of faunal remains made up a small part of the assemblage; rat and historic mammal remains (Table 7.11). Historic mammal (i.e., sheep) remains make up a significant proportion of the total weight (14.3%) which is a function of their larger size and greater mass. These materials also included the remains of a

Table 7.11 Relative abundance of faunal remains at Site 6–58

Resource	Phase 1	Phase 2/3	Phase 4
Fish	16, 286	1214	812
Bird	2057	422	117
Rat	433	11	11
Mammal	355	79	1146
Total	19, 131	1726	2086

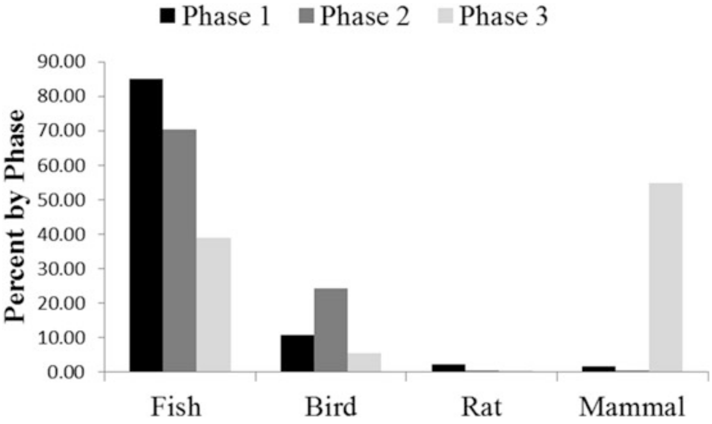

Fig. 7.8 Faunal remains by phase at Site 6–58

child in Test Unit F, Level 6, represented by an ulna, radius, and several ribs. The disarticulated condition of the child skeleton suggested that the bones were being used as raw material for tools such as fishhooks and needles. No additional human remains were found in the assemblage except for a fishhook recovered in Test Unit D. While the mammal remains declined in frequency toward the rear of the cave, it was noted that 776 bones, or nearly half of the mammal assemblage, were recovered from the upper excavation levels of Test Unit F. A total of 620 (22.06 g) bones were recovered from the historic level (Phase 4). These remains reflect a disposal event of a sheep.

Rat remains accounted for less than 2% of the assemblage (Table 7.10). A few of the bones show evidence of burning, but it cannot be determined if all of the elements were culturally introduced or represented a natural death and decay of the rodent.

We postulated that a change in subsistence may have occurred with the transformation of the cave to an AMC. The percent occurrence for each faunal category accumulated during the Phase 1 occupation is shown in Fig. 7.8. Here, we see that fish remains dominate the assemblage and constitute 85.9%. The second most frequent occurrence are chicken/bird remains (9.9%) followed by mammal (2.1%) and rat (2.0%).

The faunal assemblage is also presented in a bar graph by percent occurrence without the mammal elements since twentieth century European mammal and

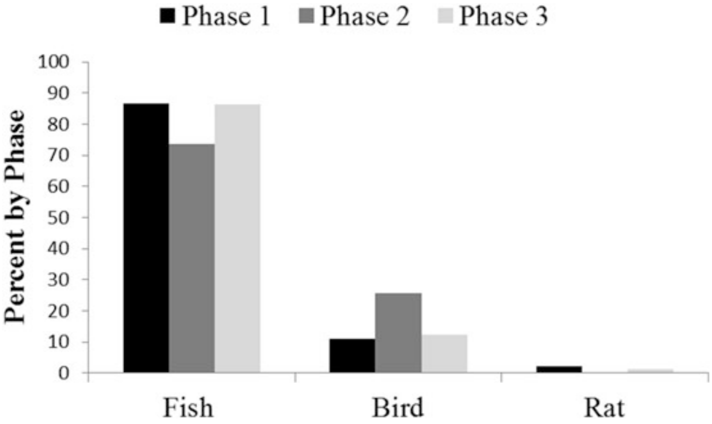

Fig. 7.9 Faunal remains at Site 6–58 excluding mammal remains

human remains were not a focus of dietary consumption during the early contact period. It can be seen in Fig. 7.9 that the historic Phase 4 assemblage is virtually identical to that of the Phase I occupation. Fish remains form 87% percent followed by chicken/bird (9.1%) and rat (1.1%). During Phase 2/3, the emphasis on fish declines slightly and chicken is emphasized. These small differences, however, do not support a significant shift in the consumption of faunal resources between difference occupations at the site.

10 Discussion

It is our working hypothesis that AMCs represent a secluded space where contestants (*hopu*) in the Birdman competition prepared themselves physically and spiritually for this annual leadership ritual. The evidence to support this hypothesis is indirect and in making our inferences we rely on generalizations about human behavior which may or may not have been operative in the past. Thus, we do not arrive at a firm conclusion but suggest only that the evidence is supportive and not definitive. This awaits additional research.

Our cross-cultural analysis of ethnohistoric refuge caves on the island of Samoa highlighted numerous differences between these places and the refuge caves (*ana kionga*) of Rapa Nui. Refuge caves on these other islands tended to be geographically isolated and visually difficult to identify. The interiors were spatially large, and there is archaeological evidence of domestic occupation and architectural evidence for internal structural modifications to increase defensive capability. Such caves may indeed be present on Rapa Nui if the survey inventories (McCoy 1976; Stevenson and Haoa 2008) are reviewed in detail. The Rapa Nui *ana kionga* differ on all accounts. Although the total number of AMCs is not known, within surveyed areas they are numerous in occurrence and are located within the lowland settlement pattern, and in many cases within the core areas of domestic settlements (Stevenson and Haoa 2008). While the entrances are small, they are formalized through the use of shaped stone that contrasts with the surrounding landscape. The interiors are small, poorly illuminated, and frequently damp. The interiors contain features such as platforms and secondary rooms but no additional defensive architecture such as interior walls. These remarkable differences caused us to reconsider the interpretation of *ana kionga* as refuge caves.

The architectural similarity of the AMC with the stone houses at ‘Orongo and the presence of AMC on the islet of Motu Nui prompted us to hypothesize that the mainland AMCs were connected to the Birdman Cult and the process of leadership selection for the island in the post-European contact period. Routledge (1919) describes one cave occupied by contestant *hopu* on one of the islets just before the arrival of the terns. She states:

“The *hopu* lived together in a large cave of which the entrance is nearly concealed by grass. The inside, however, light and airy; it measures 19 feet by 13 feet, with a height of over 5 feet, and conspicuous among other carvings in the center of the wall is a large *ao* more than 7 feet in length” (ibid: 261).

Unfortunately, this description contradicts our thesis that AMCs are small, damp, and dark, but it does reinforce the idea that caves associated with Birdman Cult activities are marked by symbols, in this case where the *ao* is a marker of chiefly status.

Although the origin of the Birdman Man cult may have a seventeenth century origin the archaeological evidence for its formation is lacking, but it is clearly in place and active in the late eighteenth and nineteenth centuries (Robinson and Stevenson 2017). The only physical evidence that links AMC to ‘Orongo is the architecture of the AMC opening. Images of *Makemake* are pecked into the cave wall, but they cannot be stratigraphically linked to the occupation of the AMC. Nevertheless, the new chronological determinations converge with the occupation of ‘Orongo and unique archaeological features, such as white clay flooring, which differ from other domestic habitations, argue for the creation of a ritual context that may have been used by contestants in the Birdman annual ceremony to prepare themselves for the competition to retrieve the egg of the Sooty tern, an egg which encapsulated the spirit of the deity *Makemake*.

Chronological determinations at Site 6–58 place the use of AMC at the same time as activities at ‘Orongo. These data consist of obsidian hydration and AMS dates that support a peak nineteenth century occupation. The radiocarbon dates from above (Phase 2/3) and below (Phase 1) the white clay floor have the greatest probability of occurrence in the nineteenth century with some less consistent occupation in the 17th-early 18th century. The obsidian hydration dates offer some additional clarity. The deepest cultural layers produced obsidian dates from the thirteenth to seventeenth centuries (Phase 1) and reflect the long-term use of the cave. The shallow cultural deposits suggest limited or short-term occupations without a lot of refuse accumulation unless later modifications removed soil material. The next 20 cm of soil deposits reflect middle eighteenth to early nineteenth century deposition although a few dates are a century earlier. These layers are capped by the white clay floor of imported montmorillonite that was installed in the very late eighteenth century or early nineteenth century. The dates above the floor reflect the same temporal range.

The installation of a white clay floor within the AMC is especially indicative of the desire to change the everyday context into a unique setting. The entrance to the cave was sealed with a high wall and access restricted by a tunnel entrance. White montmorillonite was likely mined from exposed stratigraphy in a cave near Vinapu (Métraux 1940: 236) and spread out in the front half of the AMC to form a living surface which was refurbished at least once. Floors of this type were not identified in any of the numerous caves excavated by Ayres (1975) but did occur in the nearby AMC of Site 6–357 where the floor was refurbished six times (Stevenson et al. 2019). The limited occurrence of white clay flooring suggests a use not connected with daily life, and the periodic refurbishment suggests that it was event driven on a periodic basis. What is becoming increasingly obvious is that the ancient Rapa Nui would "ritually close" a structure such as an *ahu* by covering the surface with scoria (see Cauwe this volume). The reapplication of white clay floor could reflect a similar behavior, which, in this case, marks the end of the birdman ceremony for that year.

We will push our speculation forward a bit (to an almost unbelievable limit) and suggest that the inside of the AMC with its white floor and black ceiling may reflect the black and white coloration of the Sooty Tern. And taken even a step further, the cave may even represent the egg of a tern with its white shell within which resides the spirit of the god *Makemake*.[1]

What were the ancient Rapa Nui doing in the unmodified cave and later in the AMC? The faunal and lithic assemblages provide some clues. The bone and stone tools recovered from Site 6–58 reflect a limited diversity of technologies. Recognizable bone tools include only fishhooks and needles, the majority of which are associated with the Phase 1 occupations. The absence of fishhooks and only the recovery of two needles in the Phase 2/3 deposits could be a result of limited loss and discard as a result of shorter occupational duration or a lesser emphasis on fishing and the maintenance of fishing gear. Other bone tool forms such as harpoons or awls/perforators are not present nor are there any decorative pendants. Fishing might have occurred with hand lines or nets from elevated shore locations much like casual fishing is conducted today.

The obsidian assemblage from the cave is substantial. The greatest contribution comes from the Phase 1 deposit with its large number of tertiary flakes and flake fragments. Large nodules of raw material are absent, but two core fragments were present. This limited evidence suggests that prepared cores were brought to the site and flakes were produced as required. The same interpretation is proposed for the Phase 2/3 assemblage which is numerically small with the total number of items

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[1] We would like to note that the creative mind of Dr. Paul Wallin was the origin for these possible interpretations and we thank him for his originality.

only being a few hundred items. Approximately 38% of the obsidian is fragmentary which is suggestive of reduction by percussion. This occurrence of lithic reduction in a dark enclosed cave seems incompatible with the proposed function as a ritual space, but a similar occurrence of obsidian flakes and fragments was obtained from the living floor of AMC Site 6–357 where the total assemblage from eleven test units was 34 whole flakes and 47 flake fragments (Stevenson et al. 2019). We propose that craft activities were conducted within the cave and flake tools may have been required for those sequestered persons working within the AMC.

Making sound inferences from the obsidian assemblage about past activities is difficult because of the limited tool diversity within all occupations. The two recognized flake tool categories consist of gravers which may have been used to score wood or fiber and flake side-scrapers. Each of these tools may have been used in a variety of ways on wood, plants, or food products. Complementing the flake tools were a number of broken and complete *matā* for which we have use-wear analysis (Kononenko et al. 2019). In the Phase 1 deposits margin-sawing/whittling/scraping of woody plant material was identified along with the sawing/whittling/scraping of shell/bone which is consistent with the manufacture/maintenance of fishing equipment such as fishhooks. Numerous bone needles were present that may have been used in the making or mending of fishing net.

In the Phase 2/3 analyzed obsidian associated with the AMC are the *matā* and utilized flake where use-wear identified the working of woody plant material. These woody materials may have included soft and hard woods, palm fiber, reeds, and hard grasses (Kononenko et al. 2019:71). The use-wear work of Church and Ellis (1996) attributed obsidian edge damage to fresh green plants as well. The working of wood and fibers in a dark confined space places limits on the scale of possible activities. It is likely that crafts were only conducted by a few people, and we suggest it would have been limited to the making of personal items of clothing, headdresses, caps, woven matting, or containers. The presence of a few bone needles gives this some support.

Evidence for food consumption was reflected in the extensive faunal assemblage. Fish remains in great abundance are present in Phase 1 and support the use of the cave as a location to relax between fishing activities. Chickens were not likely raised at a location directly on the shoreline and their bones reflect foods imported from inland domestic sites. The density of faunal remains suggests that the cave was not regularly cleaned and this behavior is characteristic of places that are occasionally visited and where waste management is not needed.

Fish are also plentiful in the diet of the occupants of the AMC, and refuse buildup on top of the white clay floor was also substantial in this confined space. In the case of AMC Site 6–357, there is evidence to show that food refuse was covered over by another application of white clay, but at Site 6–58 this behavior was not identified in the micro-stratigraphy of the floor. It may be that the AMC was abandoned for extended periods and the unpleasant odor of decaying food was avoided. If this evidence for behavior of periodic abandonment is correct, then it may indicate that ritual seclusion only occurred when a suitable contestant for the Birdman cult became available.

The data set discussed here hold additional clues about the activities of AMC. The faunal assemblage needs to be analyzed as to species to determine if food preferences were operative and if consumption of the sooty tern, for example, was symbolically included into the ritual process. Additional use-wear and residue analysis also has the potential to be more specific about craft activities conducted within the cave.

11 Conclusions

AMCs are small and dark enclosures where the occupants are isolated from the larger public. They represent intentional transformations with a substantial investment in the stone architecture and interior features that are different from other caves used in daily life. They are special underground places where the occupants are not distracted by the secular. These places appear to have originated near the time of European contact. We propose the AMCs are one component of the Birdman Cult which was a development emerging from the earliest of contacts, the physical and psychological trauma of those contacts with Europeans, and the illness that they left behind. The occupants of the AMC may have been competitors for the office of Birdman. The contest would have required physical and spiritual preparation and the AMC would have been a place to contemplate and emotionally prepare for a new social role. But the archaeological evidence often associated with ritual preparation such as tattooing, scarification, body adornment, intoxication, sacrifice, or specialized diets has not yet been found. Site 6–58 and Site 6–357 were excavated without this research question in mind, and other approaches are required. The answers are within and on the surface of the white clay floor.

Acknowledgments We wish to thank the Consejo de Monumentos Rapa Nui and the Consejo de Monumentos Nacionales de Chile for their permits to conduct excavations on Rapa Nui. We are also grateful to William Ayres and Katie Rorrer for their analysis of the faunal material. Robin Torrence eagerly supported and promoted the obsidian use-wear analysis, and Nina Kononenko completed a thorough and detailed analysis of the obsidian *matā* for which we are very grateful.

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Chapter 8
Vinapū Area Re-visited

Helene Martinsson-Wallin

1 Introduction

In the southwest corner of Rapa Nui in a small valley, facing the seashore towards the northeast, is an area called *Vinapū* (Fig. 8.1). Two prominent ceremonial sites (*ahu*) are situated in the valley mouth close to the rugged cliff shoreline that is 27 masl. The terrain is sloping from the volcanic crater of Rano Kao, where the ceremonial village of Ōroŋo is situated at an elevation of ca. 400 masl and about 3.2 km south-southeast of Vinapū. On the north-northwest side of the Vinapū valley about 1.1 km from the two *ahu*, the summit of Mount Orito is situated at an elevation of ca. 94 masl. Two elite villages with kerbstones foundations (*hare paeŋa*) are located on higher ground overlooking the two large ceremonial sites towards the east. An additional smaller *ahu* structure is situated about 200 m to the north of the two ceremonial sites on a small summit at 47 masl (see Fig. 8.2a, b).

The American archaeologist William Mulloy, who participated in Thor Heyerdahl's archaeological expedition to Rapa Nui in 1955–1956, investigated the two larger *ahu*, the elite village no. 1, and several stone platforms and a tomb in the Vinapū area (Mulloy 1961:93–180). A charcoal sample from a lens found under the earthen embankment surrounding the plaza of *ahu* 2 (Trench 22) gave a date of BP 1100 ± 200 (M-710). To re-assess the accuracy of this date, I carried out a re-excavation in the area during 2 weeks in 2002 (Martinsson-Wallin 2002, 2004a). My research on Rapa Nui prehistory has revolved around questions of early settlement and the development of the ceremonial architecture (Martinsson-Wallin 1994, 1998, 2000, 2004b, 2007; Martinsson-Wallin et al. 2013). The early date from under the embankment was considered to be of interest for a further investigation to address

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_8

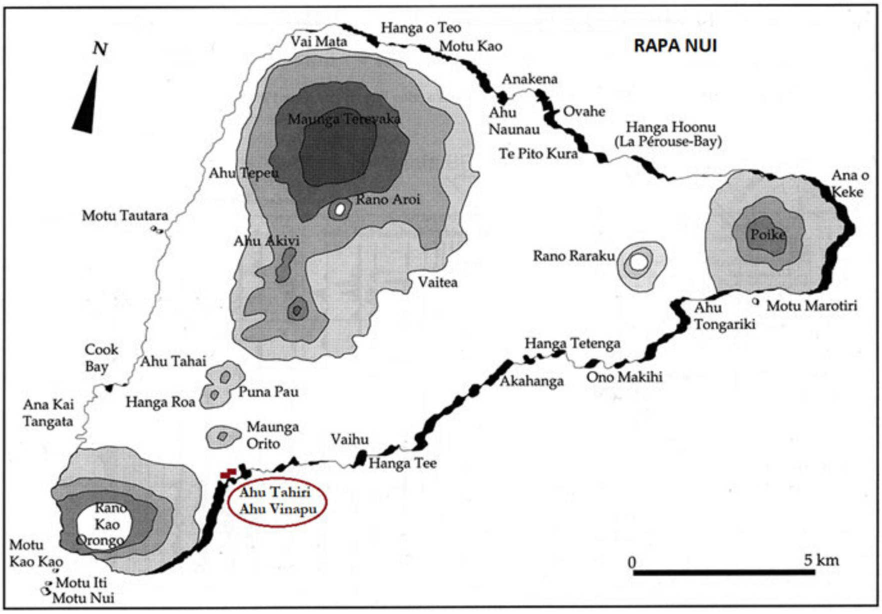

Fig. 8.1 Map of Rapa Nui with the Vinapū *ahu* structures indicated (©Paul Wallin and Helene Martinsson-Wallin)

the above research topics. Aside from the re-assessment of the temporal status of the charcoal lens, the aim of the re-excavation was to obtain data on the limits and context of this cultural activity. In addition, we excavated a number of test trenches in the surrounding area to understand the stratigraphy and relationships of the archaeological remains in the Vinapū area. This paper presents and discusses the results from the investigations of the Vinapū area, with the aim of understanding the chronology and diachronic aspects of ceremonial sites and the social relationships on Rapa Nui.

2 Earlier Investigations and Accounts

William Mulloy carried out archaeological investigations in the Vinapū area between November 27, 1955, and April 6, 1956. He published these investigations in the volume *Archaeology of Easter Island Volume I* edited by Thor Heyerdahl and Edwin Ferdon (Mulloy 1961:93–180). Mulloy did rather detailed excavations, reconstructions and some restorations at *ahu* no. 1 (1961:95–115), which according to local informants is called *ahu* Tahiri. This *ahu* is famous for its high-quality stonework of the platform wall facing the sea and Thor Heyerdahl (1961:498–500) has compared this workmanship as similar to an Inca wall. Furthermore,

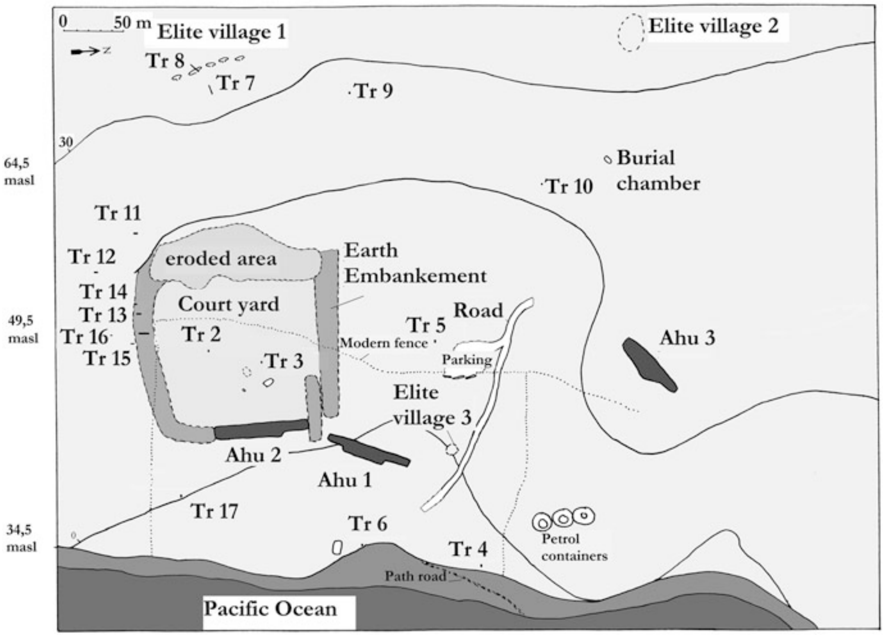

Fig. 8.2 (**a**) Map of Vinapū area with trenches from excavations in 2002 (©Paul Wallin and Helene Martinsson-Wallin). (**b**) Close up map of *ahu* structures Tahiri and Vinapū II with trenches from excavations in 2002 (©Paul Wallin and Helene Martinsson-Wallin)

Mulloy partially excavated and made suggestions for the reconstruction of *ahu* no. 2 (1961:115–135), the elite village no. 1 (1961:135–146) and an isolated tomb (1961:147, 150).

Concerning the landscape surroundings of the *ahu* structures, Mulloy reports (1961:93) that the cliff on which the two *ahu* are situated have caves and cavities but it is likely that the cliff edge has collapsed through erosion due to past activities that removed trees and vegetation. There is local information on human skeletal remains that have been found in the caves below the cliffs edge but they were likely placed there after the smallpox epidemic of 1864 (Mulloy 1961:93).

The cove below the cliff has been used as a harbour. Mulloy (1961:93) hypothesises that the remains of a masonry wall could have served as a landing place for transported of statues that were moved from the statue quarries at *Rano Raraku*. This beach has smoothed water-washed pebbles and cobbles of dark basalt called *poro* (Fig. 8.3). Elite house patio pavements and fill layers in *ahu* crematoria show such *poro* stones. Mulloy furthermore notes (1961) that the Vinapū valley has fewer stones distributed on the surface than in many other places. The agricultural features called "rock gardens" (Stevenson and Haoa 2008), areas where humans have accumulated rocks for agricultural purposes to retain moisture and provide nutrition for the soil to improve the condition of plants and plant growth, was not a concept when Mulloy was carrying out his investigations in the 1950s. Thus, the

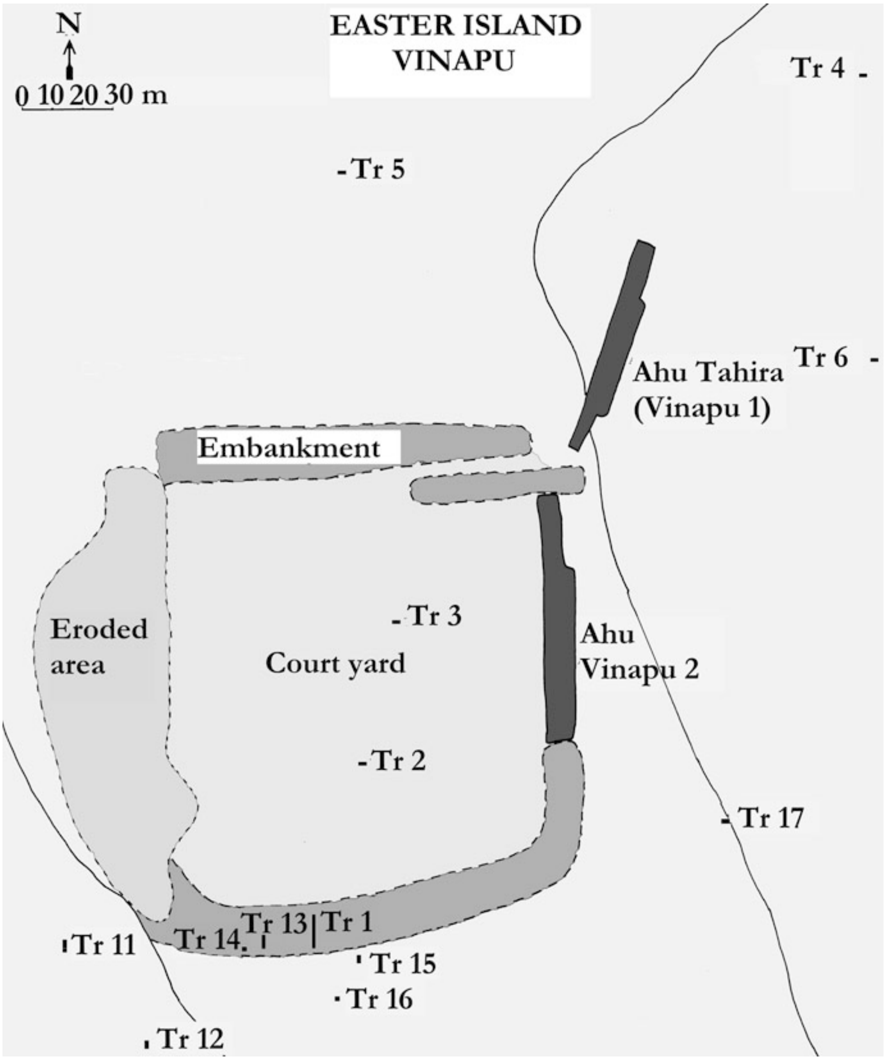

Fig. 8.2 (continued)

absence of accumulated stones on the surface could indicate that the Vinapū valley was a ceremonial and elite residence area (compare it to the Anakena area, this volume) and not a place for agriculture. However, Sr. Rafael Rapu, who was the foreman during my excavation in 2002, informed me that the area had been used for growing corn in historical times and the building of the airport close by might have had an effect on altering the landscape. The investigation by Mulloy (1961:94) showed the presence of extensive root molds in eroded and excavated areas, which

Fig. 8.3 Sra. Susanna Nahoe on a beach with *poro* at Vinapū (photo © Helene Martinsson-Wallin)

is evidence of that the area once had an abundance of vegetation (see discussion below).

Mulloy furthermore noted that (1961:94); "a line perpendicular to façade of Ahu no. 1, however, points in a true azimuth of 114° east of north. This is within 2° of the true azimuth of the rising sun at the southern summer solstice (116°)". The interpretation by Mulloy (1961:94) is; "These apparent astronomical relationships imply considerably knowledge of, and interest in, such phenomena on the part of the builders". There could be a connection between celestial events and the outline of *ahu* Tahiri. Subsequent to Mulloy's observation, Liller (1993) has discussed the archaeoastronomy and celestial events tied to ceremonial sites in Rapa Nui. I have myself experienced the phenomenon of perpendicular alignment of the rising sun at the southern summer solstice at *ahu* Tahiri and it is very likely that celestial phenomenon of various types have been important to the ancient Rapanui people (Fig. 8.4).

Mulloy was not the first to conduct excavations in the *ahu* structures at Vinapū. Paymaster William J. Thomson did small excavations (*looting!*) in *ahu* Tahiri in 1886 (Thompson 1889:511–12). Thomson notes that: "The sea front is built of immense blocks of hard heavy volcanic rock, smoothly faced and neatly joined together... it was thoroughly investigated at the expense of great labor and time"

Fig. 8.4 Summer solstice sunrise at *ahu* Tahiri, a visit organised by Sr. Hetereki Huke in 2008 (photo © Helene Martinsson-Wallin)

(1889:511). It is evident that the primary purpose of Thomson's excavation was to find human remains. "To our disappointment, we had nothing to show for the great labor extended upon this platform. The only human remains about the place are those of recent date, in shallow tombs in the rear side of the pile" (1889:512). Thomson furthermore recounts a legend that this *ahu* was the last one built on the island and that the giant statue (*el gigante*) that is still unfinished at the quarries in *Rano Raraku*, was destined for this platform. The legend indicated that there was a feast at the platform and the high chief's wife who was from the *Tongariki* clan was not given the part of the "long pig" (roasted human) that she anticipated and this started wars between the clans and ended the construction of the ceremonial sites and statues at this site (Thompson 1889:512). Thompson (1889:512–13) and his crew excavated the plaza of *ahu* no. 2 as well, but no finds were reported from this site.

In addition to Thomson's and Mulloy's investigations, some ethnohistorical accounts mention visits or sightings of the *ahu* structures at Vinapū. Forster Sr. who participated in James Cook's second voyage, that made a brief call to Rapa Nui in 1774, visited *ahu* Tahiri and observed three fallen and fours standing statues (Forster 1777:586). The Russian commander Lysianskyi who called at the island in 1804, noted four standing statues on one *ahu* and three on the next *ahu* in Vinapū (Lisiansky 1814:83–85). An additional Russian expedition led by Kotzebue called at the island in 1816 and he notes only two statues standing at Vinapū (Kotzebue 1821:55). When the missionaries arrived in 1864, no statues remained

Fig. 8.5 Aerial photo of *ahu* Tahiri, courtesy of Don and Elaine Dvorak (1996 KAP 106-print 28)

standing at Vinapū. Horley (2010:57–65) has made a computer model of what *ahu Tahira* once could have looked like with all the statues standing based on Mulloy's reconstructions using Don and Elain Dvorak's aerial photos (Fig. 8.5) and ethnohistoric and oral accounts.

The British battleship *Topaz* visited the island in 1868 and the surgeon Palmer (1875:296) notes that the natives had constructed a "roof" over three of the overthrown statues to make a vault at *ahu* Tahiri. Palmer furthermore attests (1868:373–374) to the finding of several skeletons at the site and adds a description and drawing of a "cremation stone"; a red scoria column with two heads used for offering of burnt sacrifice found at Vinapū (1875:284). Mulloy's team found it on the ground at *ahu* no. 2 and raised it up again.

3 Mulloy's Investigation of the Ceremonial Sites in the Vinapū Area

3.1 Ahu Tahiri (ahu no. 1)

There are three ceremonial sites in the Vinapū area (see Fig. 8.2). Mulloy focused his investigation on *ahu* Tahiri (*ahu* no. 1) since it had exceptional stone workmanship exemplified by the stone blocks of the seaward wall that have a smooth surface and perfect joining of the large and dense basalt stone boulders (Mulloy 1961:94–114). Mulloy indicates that changes in the *ahu* architecture are tied to three cultural phases. Based on the investigations of various remains on the island by the archaeologists who participated in Heyerdahl's archaeological expedition, they were influenced by the prevalent cultural historical theoretical approach and divided the cultural sequence on Rapa Nui in an *Early Period* dated to AD 400 (?)–1100 (?), a *Middle Period* ranging from AD 1100 (?)–1680 and a *Late Period* from AD 1680–1868 (Ferdon 1961:527–533). However, Mulloy did not see any evidence of a time interval between the Early and Middle Period at Vinapū, and he states that even if there is "disorganization and disintegration of certain religious or ceremonial activity in the Late Period, there is no evidence that new groups of people were involved" (Mulloy 1961:111). He interpreted the toppling and destruction of statues as well as the dismantled elite houses (*hare paeŋa*) as acts of hostilities among clan groups in the Late Period.

Mulloy writes (1961:111) that all statues of *ahu* Tahiri (Table 8.1) are tipped landward and the three northernmost statues displaced the Middle Period rough stone-wall on the inland side and the "second and third from the south fell over a large Early Period basalt slab which was retained in the inland side wall during Middle Period times". He is of the opinion that the demolished *ahu* had potential for restoration by the clan group whom it belonged to but he notes that only one statue was sufficiently undamaged to be re-erected. However, the "vault" mentioned by Palmer (see above) is probably the same as the enclosed construction of the three southernmost statues reported by Mulloy (1961:112, Fig. 18). The Rapanui used uncut and cut stones from *ahu* and elite houses alike to make this modification.

Mulloy's team found scattered human remains covered by stones in the *ahu* ramp but he notes; "thickly scattered stones had apparently been deposited deliberately in places where there was no evidence of burials. It appears as if the people were not only placing inhumations here, but were deliberately trying to cover up the *ahu*" (1961:114). Hiding and burying statues and the *ahu* is discussed by Ayres et al. (2014) for *ahu* Ura Uranga te Mahina (see further discussion below and Cauwe this volume). Only two *pukao* (topknots) have been found at *ahu* Tahiri but it is likely that all seven statues once had topknots (Table 8.2).

According to Mulloy (1961:100–101), construction of the *ahu* Tahiri platform began at the centre of the structure in the Early Period by placing layers of large boulders in a 1-m deep excavation and then placing a line of irregular rectangular slabs in a horizontal position on top. The worked slabs of the seaward wall were then placed on this sturdy foundation. According to Mulloy, the seawall slabs that weighed many tons must have been worked to a perfect fit at the site (1961:103). On the inland side, a stone fill supported the seawall but the nicely cut *paeŋa* seen in many *ahu* front retaining walls seems to be missing here. The careful levelled construction and the stone masonry workmanship of this central platform are indicative of highly skilled builders who knew what they were doing. Mulloy never questioned if the ramp, wings, the second tier of the seawall were additions to an initial platform that could have had a flat paved area instead of a ramp on the inland side. However, Mulloy suggests the ramp had two phases of construction and a charcoal sample from what he interprets as the "first mantle" of the ramp was dated to BP 440 ± 100 (K-523, see Table 8.3) (1961:99). Furthermore, he notes that

Table 8.1 Estimation of measurements and weights of the toppled statues (*moai*) at *ahu* Tahiri and Vinapū II made by Mulloy (1961)

Ahu	Moai no. Englert	Moai later inventory	Height (m)	Basal breath (m)	Weight (kg)	Comment
Tahiri	620		3.64	2.10	8190	See Fig. 8.5
Tahiri	621		4 (?)	2.10	10,920	See Fig. 8.5
Tahiri	622		6.5 (?)	2.60	38,220	See Fig. 8.5
Tahiri	623	2–210-03	5 (?)	2.15	20,020	See Fig. 8.5
Tahiri	624	2–210-02	5 (?)	2.05	20,020	See Fig. 8.5
Tahiri	625	2–210-01	4.40	1.80	14,560	See Fig. 8.5
Tahiri	626		2.70	1.70	3276	See Fig. 8.5 (partially buried statue on the seaward side)
Vinapū II	631		x	x	x	The northernmost
Vinapū II	I (the number not visible)		x	1.40	x	
Vinapū II	634		x	1.90	x	
Vinapū II	635		4.20	2.20	12,558	
Vinapū II	636		4.30	1.90	14,014	
Vinapū II	637		3.90	2.00	x	
Vinapū II	638		x	2.40	x	
Vinapū II	639		x	x	x	
Vinapū II	II (the number not visible)		2.20	1.10	1.820	

Table 8.2 Estimation of the measurements and weights of the topknots (*pukao*) at *ahu* Tahiri and Vinapū II made by Mulloy (1961)

Ahu	Pukao no. Englert	Diameter (m)	Height (m)	Weight (kg)	Comment
Tahiri	x	1.80	1.60	6095	Probably belong to statue 624
Tahiri	x	1.60	1.70	5399	Probably belong to statue 623
Vinapū II	630	1.60	1.20	4317	
Vinapū II	632	1.70	1.20	4873	
Vinapū II	633	1.60	1.10	3957	
Vinapū II	640	1.50	1.30	4110	
Vinapū II	III (the no. is not visible)	1.80	1.20	5463	

on "the seaward side of the *ahu* a pavement made of a double row of cobbles was laid … There was no evidence of a similar paving on the land side" (1961:104). Concerning the statues, Mulloy is of the opinion that there is no evidence of statues from the Early Period construction and he concludes that "The general appearance of the Early Period structure suggests a gigantic open-air altar" (1961:105).

3.2 Ahu no. 2

This *ahu* is situated to the south of *ahu* Tahiri and was investigated by Mulloy and his team (1961:115–135) but not in the detailed manner as the former. Due to lack of time, they mainly investigated the northern part of the *ahu* and the embankment surrounding the plaza. The *ahu* structure diverges from *ahu* Tahiri in several ways but the most noticeable is the lack of worked and perfectly fit slabs in the seawall and that almost the entire *ahu* had been covered up with stones during the Late Period. Furthermore, among the stones, there were discoveries of a large number of rather well-preserved human remains that subsequently were analysed (Mulloy 1961:115; Murill 1965:255–324).

The central seawall is comprised of a row of upright stones with un-worked surfaces of various heights (ca. 120–200 cm) but the top surface is rather level since the ground surface is higher in the south and lower in the north (Heyerdahl and Ferdon 1961, Plates 9d, 12a, b and Figs. 133–35). Generally, the uprights of the seawall show very little modification for close fitting or smoothing of the surface but there are indications of small positional adjustments of the joint between the stones, or selection of stones, to get a good close fit. The stonework and appearance is quite different from *ahu* Tahiri, but Mulloy suggests (1961:119) that it had a similar type of substructure to hold the weight of seawall but without the horizontal slab footing. He further suggests that the seawall originally had fitted capstones on top of the uprights to make a level surface but that these capstones were removed in the

Table 8.3 Radiocarbon dates from the Vinapū area (Calibrated with: OxCal 4.4, SHCal 20 calibration curve)

Sample No.	Collector	Provenience	Date BP	Material	Calibrated AD 1σ	Calibrated AD 2σ	Year	Comments
Ua 19465	Martinsson-Wallin	Uphill Vinapū area Trench 13 feature 1	BP 280 ± 45	Charcoal	1515–1799	1503–1809	2002	Likely from clearing of land of palm trees
Ua 19463	Martinsson-Wallin	Embankment, Vinapū II Trench 1 Feature 4	BP 610 ± 40	Charred nutshell	1323–1416	1304–1437	2002	Under embankment Vinapū II
Ua 19464	Martinsson-Wallin	Embankment Vinapū II Trench 1 Feature 7	BP 605 ± 45	Charred nutshell	1323–1421	1303–1442	2002	Sample close or from the same feature as Mulloy's sample M710
T-5175	Skjølsvold and Figueroa	Vinapū II crematoria	BP 570 ± 120	Charcoal + ash	1294–1480	1233–1635	1984	Was excavated in 1982: broad range
M 710	Mulloy	Vinapū II Under embankment	BP 1100 ± 200	Charcoal	774–1178	598–1377	1957	Sample close to or same as Feature 7
M 711	Mulloy	Ahu Tahiri crematoria	BP 730 ± 200	Bone (human)	1054–1446	897–1643	1958	Broad range, difficult to use
M 709	Mulloy	Ahu Tahiri phase III	BP 120 ± 200	Charcoal	1668–	1464–	1957	Surface collection on the late ramp. Broad range, cannot be used
K-523	Mulloy	Ahu Tahiri phase II ramp	BP 440 ± 100	Charcoal	1430–1627	1321–1798	1956	Broad range

? "is uncertain or approximate measurement" that base on Mulloy's data

Middle Period (1961:105). Concerning the Early Period features, Mulloy concludes that (1961:121) the plaza and the embankment seem to be part of the early structure. A charcoal sample dated to BP 1100 ± 200 (M 711, Table 8.3) from a fireplace covered by the embankment supports this assumption. The early dated charcoal sample under the embankment and this platform is subject to re-assessment and a further discussion follows below.

Mulloy suggests an abandonment of *ahu* no. 2 is due to erosion followed by vandalism and the removal of capstones of the central section during in the Middle Period. He notes the possibility that stones from *ahu* no. 2 were re-used in *ahu* Tahiri (1961:105). The re-building of the site seems, according to Mulloy, to focus on the placing of statues on top of the platform, and not the workmanship of the stone masonry, and construction details provide evidence that "statues were not raised until the Early Period wall had been destroyed" (Mulloy 1961:105). Martinsson-Wallin (1996:43) suggest that the "coral bowl" found in the ramp is a statue eye and several rounded discs found at *ahu* no. 2 are probably pupils to statue eyes (Heyerdahl and Ferdon 1961, Figs. 45 and 46). Nine statues were found in the area of which seven had previously been numbered by Father Sebastian Englert (1949), and two additional statues were found during Mulloy's excavation (Table 8.1).

The excavation record gives the impression of that this *ahu* and its surroundings have faced a lot of alterations and the moving around of stones, plus the re-use of the site as a burial ground, presumably in the Late Period. The remains of five topknots were found here (Table 8.2) and Mulloy mentions (1961:126) that they have a slightly different form than the ones at *ahu* Tahiri. Mulloy's team furthermore found that the red scoria upright mentioned by Palmer (1868) was associated with cremated bones. It was partly covered and found close to the plaza in a depression and is a "rectanguloid pillar about 70 cm wide by 60 cm from front to back. The fragment is about 3.50 m long" (Mulloy 1961:134). In addition, it is noted that the statue was standing up during Palmer's visit but he provided conflicting evidence as to where it originally stood. The statue seems to have been deliberately buried sometime after Palmer's visit (Palmer 1968:175; Mulloy 1961:133). Mulloy's excavation on the plaza just in front of the ramp also exposed an earlier pavement that is offset by 25 degrees to the south in comparison to the outline of the plaza surrounded by the embankment and the *ahu* (see Heyerdahl and Ferdon 1961, Fig. 133).

In 1982, Gonzalo Figueroa and Arne Skjølsvold did an excavation in the crematoria at the seaside of *ahu* no. 2, which provided a dated sample (T-5175) (see Table 8.3) (Skjølsvold 1993:90, Martinsson-Wallin and Crockford 2002, Table 8.3).

3.3 The Elite Village no. 1 and an Isolated Tomb

There are remains of two elite villages mentioned by Mulloy and he conducted excavations at one of them, and at an isolated tomb (1961:135–146, see Fig. 8.2

for the locations). Both villages had faced destruction during activities in the Late Period, but village no. 1 less so than village no. 2. The former is situated ca. 330 m west of *ahu* no. 2 on the gently sloping hillside. It consists of five boat-shaped houses outlined by cut *paeŋa* foundation slabs of dense basalt stone. Mulloy however, notes the re-building and removal of slabs and he interprets these actions as vandalism by enemies in the Late Period (1961:135). Finds of European artefacts indicate a post-contact occupation. Mulloy only excavated outside the houses but he gives a rather detailed description of the house construction. The most well-preserved house, labelled no. 2, is outlined as an elongated boat-shaped foundation made with worked and fitted *paeŋa* stone slabs. There were holes, or cupules, for wooden poles which made up a frame construction that would have supported a thatched roof. In addition, a semilunar patio of cobblestones is situated on the entrance side (Mulloy 1961:145, Fig. 32). I carried out a minor excavation outside and inside this elite house in 2002. A discussion of the implications of materialised ideology, including *ahu/moai* complex and elite houses, follows below.

Mulloy's team excavated an isolated tomb that resemble the house foundations at ʻŌroŋo, which was situated on the sloping hillside between *ahu* Tahiri and village no. 2 (1961:147, 150, Fig. 36). Skeletal remains of a human were found in this tomb and the remains were interpreted to be a male placed on his right side in a flexed position, but the head and lower right arm were missing. Two of the crew members said: "this must have been an important individual because his head was stolen for magical purposes, probably to place in a hen house to increase the yield" (Mulloy 1961:147). It is an unusual construction and Mulloy writes that there are no European artefacts associated with this structure. Two fragments of stone from a *hare paeŋa* were found in the interior wall of the structure which indicated a Late Period construction. The similarity of this structure with the ʻŌroŋo houses is striking (Mulloy 1975). They did not carry out any further investigations but a structure similar to the ʻŌroŋo houses was found at *ahu* Tahai near Hanga Roa but called a *tupa* by Mulloy (1970:14–16).

4 Re-assessment of the Archaeological Sites in the Vinapū Area

The objective of our project in 2002 was to re-assess the early date (M-710 BP 1100 ± 200) obtained from a charcoal lens found under the earth embankment surrounding the plaza of *ahu* no. 2 during excavations by Mulloy (1961:85–148) (see above). Our intention was to re-excavate and re-date this fire event to understand the extension, context and temporal status of this cultural activity. Another aim was to re-investigate the elite village no. 1 to understand if there were one or several chronological phases present at this site. The excavation included 17 trenches that together comprise an excavated area of ca. 45 m^2 (see the location of the trenches in Fig. 8.2). Most of the trenches were in the form of test pits, 2 m^2 in size, but two larger trenches were also excavated at the embankment (Martinsson-Wallin 2002, 2004a, b) and at the elite village. The investigations have been reported by Martinsson-Wallin (2002, 2004a, b), and all archaeological finds are stored at the Museo Antropologico Padre Sebastian Englert in Rapa Nui under the excavation no. 17–08. The full account of the investigation is found in the unpublished excavation report (Martinsson-Wallin 2002) but a summary follows below.

4.1 Excavation in the Embankment

4.1.1 Trench 1

We positioned a 1 × 10 m long excavation trench in the south part of the manmade embankment that surrounds the plaza of *ahu* no. 2, 2 m east of, and parallel to, Mulloy's Trench 22 (Figs. 8.2 b, 6). The top layer (c. 20 cm) of the excavation consisted of recently eroded soil where we found an obsidian *mata'a*. At the bottom of this layer, we encountered an irregular area ca. 60 × 40 cm in size containing charcoal (*feature 1*). In squares 1, 3, 5, 7 and 9, the excavation only removed the eroded soil from over the embankment, but squares 2, 4, 6, 8 and 10 were excavated to the original ground level. The embankment was made up of soil that had been pushed to the side of the *ahu* plaza to form an elevated mound to define the limits the plaza. The thickness of the embankment mound varied between 25 and 75 cm and contained no cultural remains.

Under the embankment, there followed a cultural layer of ca. 20 cm in thickness and this was the same layer from which Mulloy dated a charcoal sample (1961:146, Fig. 33). In the cultural layer, we found burnt areas with scattered charcoal, and charcoal lenses (*features 2, 3, 5, 7*) and possible planting pits or postholes (*features 4, 6*). We recovered from the cultural layer obsidian tools and flakes, some basalt flakes, a part of a stone adze (*toki*), some *poro,* and *umu* stones, a bird bone and a coral piece. Towards the bottom of the layer, the soil changed to a reddish-brown colour. It is possible that this was an effect of the fire events, but the soil appeared to exhibit a natural change in colour with increasing depth and contained more clay. The reddish-brown clay soil was 45–65 cm thick. We found traces of planting pits that penetrated this layer and we discovered roots molds from a palm tree (*Paschalicocos disperta*) in square 8. The original volcanic substratum of red/brown/yellowish clay soil sitting on the top of the bedrock appeared below this layer.

When excavating the top of the cultural layer in square 2, the workers identified the scattered charcoal found in the south side of the trench as sugarcane. This formed a thin lens close to, and just above *feature 6* (Fig. 8.6). This feature was a 30 × 40 cm rounded area with soft soil and about 105 cm deep. It projected slightly towards the northeast and had a rounded bottom. The fill in the pit consisted of loose brown soil, a few stones and some charcoal fragments. Among the charcoal fragments were burnt nutshells from a large palm tree (*Paschalococos disperta*).

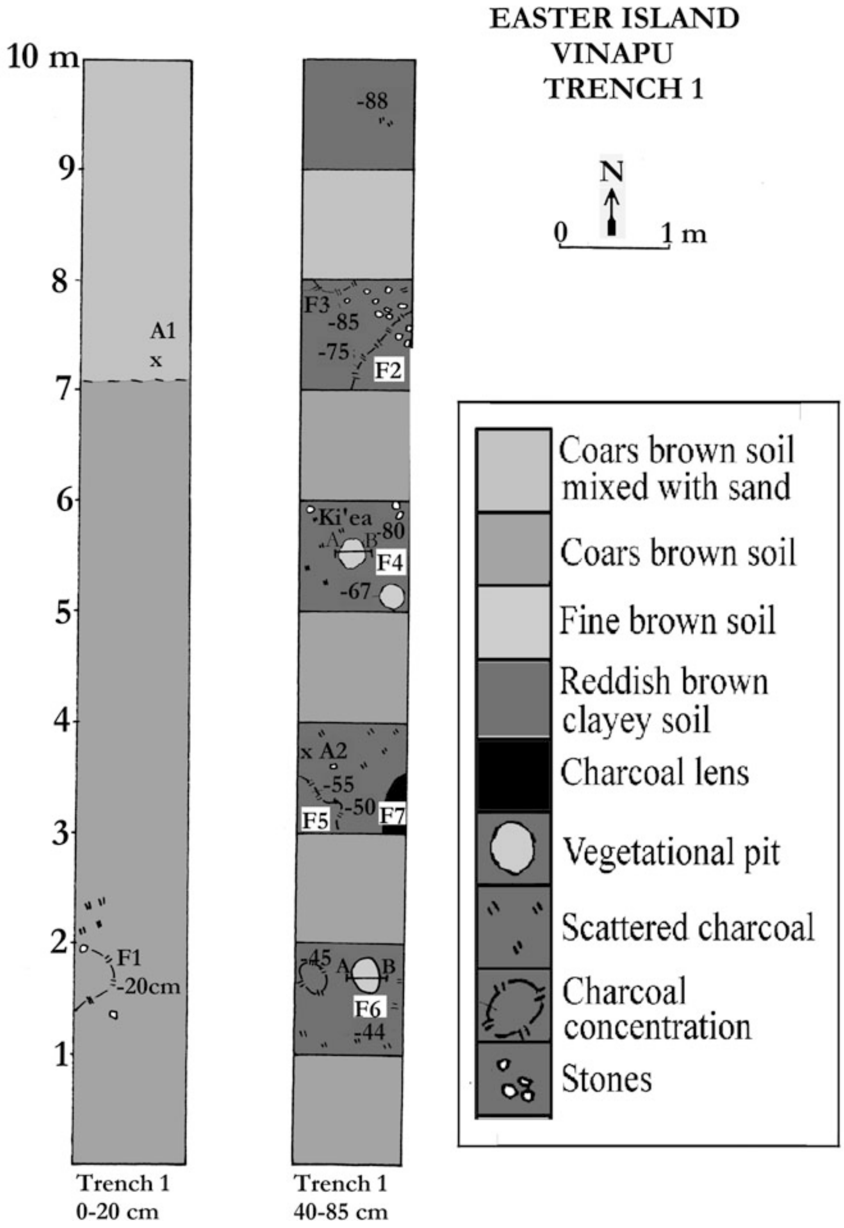

Fig. 8.6 Trench 1 during the 2002 excavation (©Paul Wallin and Helene Martinsson-Wallin)

Fig. 8.7 Feature 4 in Trench 1, sqm 6, which was a 20 × 20 cm rounded area with darker coloured soft soil that extended to a depth of 80 cm. This is likely a planting pit. A charred nutshell was dated to BP 610 ± 40 (photo © Helene Martinsson-Wallin)

In square 4, we found scattered charcoal mixed with soil in the entire square but in the southwest corner was an irregular charcoal lens 40 × 40 cm in size and 10 cm in thickness (*feature 5*). In the southeast corner a more distinct charcoal lens 50 × 20 cm in size and 10 cm thick appeared (*feature 7*) (Fig. 8.6). It projected into the east and southerly sections, and because of its size, it might have been the same feature that was previously dated by Mulloy. A charcoal sample of nutshell (*Paschalococos disperta*) from (*feature 7*) was dated to BP 605 ± 45 (Table 8.3).

In square 6, we found scattered charcoal mixed with brown soil that covered a 20 × 20 cm area. It was 80 cm deep pit containing darker coloured soft soil with a narrow, rounded bottom (*feature 4*). The soft soil contained charcoal nutshell (*Paschalococos disperta*), obsidian flakes and a bird bone. This could be a planting pit or a posthole (Fig. 8.7). A burnt nutshell from this feature was dated to BP 610 ± 40 (Ua 19,463) (see Table 8.3). Furthermore, we found an area with a red earthen pigment (*ki'ea*) in the northeast part of the square. This pigment is found at special locations, and one such place, according to the foreman Sr. Rafael Rapu was a cave located about 300 m towards the north from this trench.

In square 8 scattered charcoal mixed with brown soil was found with a few *poro* and obsidian scrapers. The southeastern part of the square revealed a simple hearth (*feature 2*). It was 60 × 40 cm in size and 10 cm deep and defined by scattered stones. The hearth contained charcoal mixed with soil. The structure probably continued into the unexcavated areas towards the south and east to form a rounded construction. Additionally, we found another charcoal concentration with stones (*feature 3*) in the northwestern part of the square (Fig. 8.6). In square 10, a few scattered charcoal and obsidian pieces were recovered. Four obsidian samples from the cultural layer (45–65 cm) in Trench 1 gave an age range of BP 284 ± 40–376 ± 46 (AD 1718–1626) (see Table 8.4) but these do not correspond with the radiocarbon dates that are approximately 300 years earlier.

4.1.2 Trench 13

An additional trench (no. 13) 1 × 4 m in size was opened in the embankment about 10 m west of Trench 1, but only two of the squares were excavated (see Fig. 8.2b). The stratigraphic sequence was similar to Trench 1 and in the top soil, we found obsidian and basalt flakes along with a sheep bone. The cultural layer displayed scattered charcoal distributions and in some places a reddish soil. There were also several areas with softer soil that varied between 10–20 cm in diameter and 10–55 cm deep. These were interpreted as planting pits or roots of trees or bushes. An obsidian flake found in connection to these areas was dated with the obsidian hydration method (see Table 8.4) to BP 409 ± 48 (AD 1593). Root molds from (*Paschalococos disperta*) were also identified here and penetrated into the volcanic soil layer.

4.2 Excavations in Connection to the Embankment and Plaza of Ahu no. 2

Since we found traces of settlement and possible planting activities as well as the palm tree root molds under the embankment in Trench 1 and 13, the goal of making more test trenches in this area was to find out the extent and further dating of these activities and remains. With this goal in mind, we placed six trenches on the exterior side of the southern and western sides of the embankment (Fig. 8.2b). In addition, we excavated two small test trenches on the plaza (nos. 2–3) but these latter units did not expose anything of interest.

With the intention of exploring the western limits of cultural activity found under the embankment, we excavated a 1 × 2 m large trench (no. 11) that was placed upslope about 85 m west of Trench 1 (Fig. 8.2b). In the topsoil were a few obsidian flakes and 20 cm below the surface, we recovered a few obsidian tools. Below this was a layer of reddish clay soil of 45–55 cm in thickness and it contained a 20 × 40 cm thin lens of charcoal and burnt soil (*feature 1*) in the northern and upper part of square 2. The lens continued into the embankment and a few obsidian flakes and a flake tool were found in connection with this activity. A charcoal sample from *feature 1* gave a date to BP 280 ± 45 (see Table 8.3). At about 70 cm from the surface the soil changed in colour and texture and two rounded areas with softer

Table 8.4 Obsidian hydration dates from the Vinapū area (analysed by Christopher Stevenson in 2002 and revised in 2021)

Lab No.	Provenience	Rim (μm)	Temperature (°C)	%RH	%OH	A (μm^2/day @160 °C)	E (J/mol)	Rate (μm^2/year)	Date BP	Date AD	S.D.
2002–1	Tr 1 Sqm 2, 45-60 cm	1.58	22.4	0.98	0.10	1.44	86,401	0.00741	337	1665	44
2002–2	Tr 1 Sqm 2, 45-60 cm	1.62	22.4	0.98	0.10	1.44	86,401	0.00741	354	1648	45
2002–3	Tr 1 Sqm 2, 45-60 cm	1.45	22.4	0.98	0.10	1.44	86,401	0.00741	284	1718	40
2002–4	Tr 1 Sqm 2, 45-60 cm	1.67	22.4	0.98	0.10	1.44	86,401	0.00741	376	1626	46
2002–5	Tr.7 Sqm 6, 0–20 cm	1.65	22.4	0.98	0.10	1.44	86,401	0.00741	367	1635	46
2002–6	Tr.7 Sqm 6, 0–20 cm	ND	22.4	0.98	0.10	1.44	86,401	0.00741			
2002–7	Tr.7 Sqm 6, 0–20 cm	ND	22.4	0.98	0.10	1.44	86,401	0.00741			
2002–8	Tr.7 Sqm 6, 50–75 cm	1.8	22.4	0.98	0.10	1.44	86,401	0.00741	437	1565	50
2002–9	Tr.7 Sqm 6, 50–75 cm	1.64	22.4	0.98	0.10	1.44	86,401	0.00741	363	1639	46
2002–10	Tr.7 Sqm 6, 50–75 cm	2.1	22.4	0.98	0.10	1.44	86,401	0.00741	595	1407	58
2002–11	Tr.8 House 2 10–20 cm	1.59	22.4	0.98	0.10	1.44	86,401	0.00741	341	1661	44
2002–12	Tr.8 House 2 10–20 cm	1.89	22.4	0.98	0.10	1.44	86,401	0.00741	482	1520	52
2002–13	Tr.8 House 2 10–20 cm	2.05	22.4	0.98	0.10	1.44	86,401	0.00741	567	1435	57
2002–14	Tr.8 House 2 10–20 cm	2.4	22.4	0.98	0.10	1.44	86,401	0.00741	777	1225	66
2002–15	Tr. 13 Sqm 4 50–60 cm	1.74	22.4	0.98	0.10	1.44	86,401	0.00741	409	1593	48
2002–19	Tr. 6 Under human remain	ND	22.4	0.98	0.10	1.44	86,401	0.00741			
2002–20	Tr. 6 Under human remain	1.49	22.4	0.98	0.10	1.44	86,401	0.00741	300	1702	42
2002–21	Tr. 6 Under human remain	2.13	22.4	0.98	0.10	1.44	86,401	0.00741	612	1390	59

soil (30 × 30 cm and 10 × 10 cm) appeared, which could have been planting pits but these were not fully excavated. In addition, we found root molds of the palm tree (*Paschalococos disperta)* in this layer that penetrated into the volcanic subsoil. We excavated an additional trench (no. 12) near the former, and it showed a similar stratigraphy (Fig. 8.2b). No cultural finds were encountered, but evidences of root molds of palm trees were found in layer three as above (*Paschalococos disperta*).

Three small test units 1 × 1 m in dimension (Trench 14, 15 and 16) were positioned close to Trench 13, but just outside the south embankment and they displayed a similar stratigraphy with scattered charcoal as documented above. The stratigraphy was the same as in Trench 13, but the top soil layer was a little thicker and contained obsidian flakes. Cultural layers with scattered charcoal and obsidian flakes were found in Trench 14 and 15 but not in Trench 16, which was furthest away from the embankment. Root molds from the palm tree (*Paschalococos disperta*) were found in Trench 15 but not in the other two test pits.

4.3 Seward Side the ahu Structures

On the seaward side of the *ahu* structures, we excavated three trenches (nos. 4, 6 and 17). When examining the section on the eroded cliff at the seaward side of *ahu* Tahiri we found two thin charcoal lenses and investigated this with Trench 4 (Fig. 8.2b). The purpose of the excavation was to examine the appearance, content and extent of this activity. The conclusion was that the charcoal lenses originated from natural fires and we did not find any indications of human activity.

Around 120 m to the south of the former trench on the seaside of *ahu* Tahiri, we found traces of eroded human skeletal remains close to the edge of the cliff. A part of the right upper arm (*humerus*), as well as some skull parts were visible on the surface. The *zygomatic, frontal* and *sphenoid* bones of the partly exposed *crania* had almost disappeared (see Figs. 8.2b and 8.8). On the surface were several obsidian flakes but it could not be determined if they were originally associated with the human remains. Five metres to the south of the human remains, on the same eroded surface, we recovered a *poro* used as a hammer stone.

We were able to determine through excavation that the body was placed in southwest-northeast direction perpendicular to the sea cliff edge. The individual lay on its back with the head towards the southwest and the face partly turned to the side towards southeast. The area around the skeletal remains was exposed by Trench 6. At 10–20 cm from the surface, the *maxillae* and *mandible* with teeth (in rather good condition) were found, as well as parts of the right upper arm (*radius*), parts of the left upper arm (*humerus*), parts of the *sternum* and fragments of rib bones (Fig. 8.8). The eruption and wear of the teeth, as well as the development of the cranial seams, show that it is most probable the remains of a young adult around 18–20 years of age. Due to the erosion of the bones, it was however difficult to determine the biological sex of the deceased person. We found two flakes and one used core besides the remains and three flakes of obsidian below. The obsidian

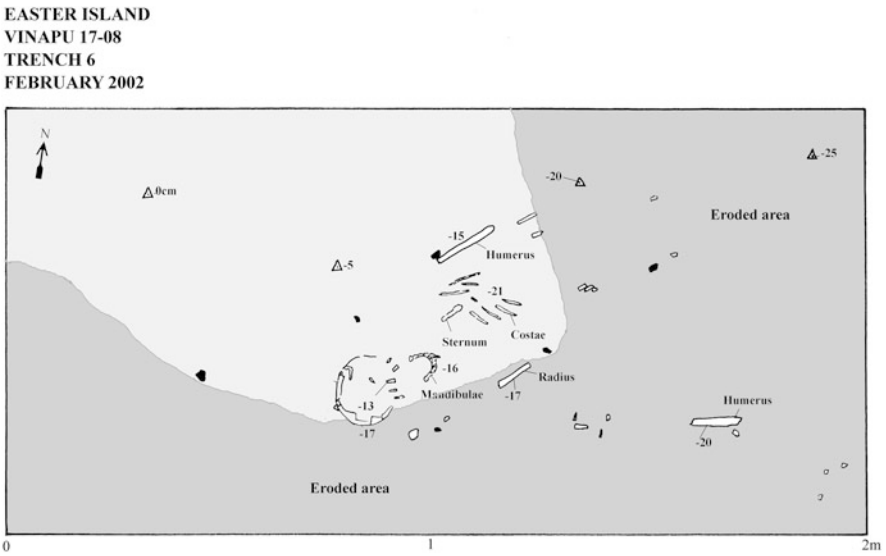

Fig. 8.8 Plan drawing of human skeletal remains found in Trench 4 (©Paul Wallin and Helene Martinsson-Wallin)

flakes found under the skeletal remains have been analysed and one indicated a date of BP 612 ± 59 (AD 1390), the other a date of BP 300 ± 42 (AD 1702) and the third gave no result (see Table 8.4). When excavating further below the remains, there were root molds, which indicates that a palm tree (*Paschalococos disperta*) and possibly other vegetation had been standing here before the skeletal remains were placed at this site. The stratigraphy was difficult to establish but besides the evidence of the palm roots, it appears that an old erosion "gully" was here. The terrain is slanting towards the edge of the cliff and was probably subjected to erosion in prehistoric times. Mulloy reported that people had been buried in the vicinity during the smallpox epidemic of 1864 and they found a human skeletal remain buried in a wooden coffin on the seaward side of *ahu* no. 2.

In addition to the investigations on the seaward side of the *ahu* we outlined a 1 × 2 m large trench (no. 17) ca. 60 m west of the rear wall of *ahu* no. 2. The stratigraphy was the same as for Trenches 4 and 6. No finds were made, but a 20 × 20 cm area with softer soil was found at a level of ca. 30 cm from the surface. The hole was ca. 40 cm deep and penetrated down into the original volcanic soil.

4.4 Excavations at Elite Village no. 1

4.4.1 Trench 7

Scattered remains of five *hare paeŋa* are situated upslope approximately 330 m NW of *ahu* no. 2 on a natural terrace oriented transversely to the slope (see Figs. 8.2 and 8.8a, b). The entrances of the houses are facing the sea and the *ahu*. To re-assess the stratigraphy, context and chronology of the elite village no. 1 a 1 × 6 m trench was excavated just next to and parallel with Mulloy's Trench 24 (1961, p. 140, 145, Figs. 8.2 and 8.8a). In squares 1, 3 and 5 only the upper 5–10 cm of the coarse brown topsoil were excavated. Materials in the upper layer consisted of an abundance of obsidian flakes, some obsidian tools, a coral file and a tooth from a pig. These finds are likely from protohistoric and modern occupations. Below the top soil, squares 2 and 4 show a mixed cultural layer of 30–50 cm in thickness. Among the finds in square 2, just beneath the top soil, were traces of a 50 × 40 cm large and 20 cm deep feature. The upper 10 cm consisted of soft dark brown soil mixed with charcoal and an abundance of burnt stones and towards the bottom there was a red brown soil mixed with charcoal but no burnt stones. Charcoal was also found distributed around the feature. The feature is interpreted as an earth oven (*umu*) (*feature 1* see Fig. 8.9b). There were many obsidian flakes and obsidian tools such as drills and scrapers, as well as some human and a chicken bone, mixed into the cultural layer and we found an obsidian *mata'a* towards the bottom of the trench. According to recent research using the obsidian hydration dating method on a large sample of *mata'a* from the Akahanga site on the South coast by Stevenson and Williams (2018) they suggest that this type of artefact was made already around AD 1400 but with a very clear peak in the late prehistoric phases around AD 1700. The majority of the *mata'a* collected by Mulloy in Vinapū area were expected to be from the late prehistoric and protohistoric time since they were mainly collected on the surface. Mulloy writes (1961:153); "There seems little doubt at Vinapū that the *mata'a* is a Late Period characteristic". However, three obsidian dates on flakes found buried at 50–75 cm in trench 7 gave obsidian hydration dates in the range of BP 363 ± 46 (AD 1639), 437 ± 50 (AD 1565), and 595 ± 58 (AD 1407) (see Table 8.4) that indicate a pre-European contact deposit. However, Lima et al. (2020) omit obsidian hydration dating from their recent evaluation of human population dynamics on prehistoric Rapa Nui as "OHDs is case-specific as it depends on the preservation/recovery of certain artifacts (lithic artifacts) from the archaeological record and is subject to spatio-temporal variations in technologies, subsistence strategies or cultural behaviors" (Lima et al. 2020:3).

In square 4, the surface sloped lightly towards the sea and under the top soil the mixed cultural layer to that in square 2 appeared. An additional earth oven (*umu*) 40 × 40 cm in size and 20 cm deep (*feature 2* see Fig. 8.9b) was found. Bones of fish, chicken and rat were found in this feature. Two obsidian *mata'a* were found together with many obsidian flakes as well as some obsidian and basalt tools and a

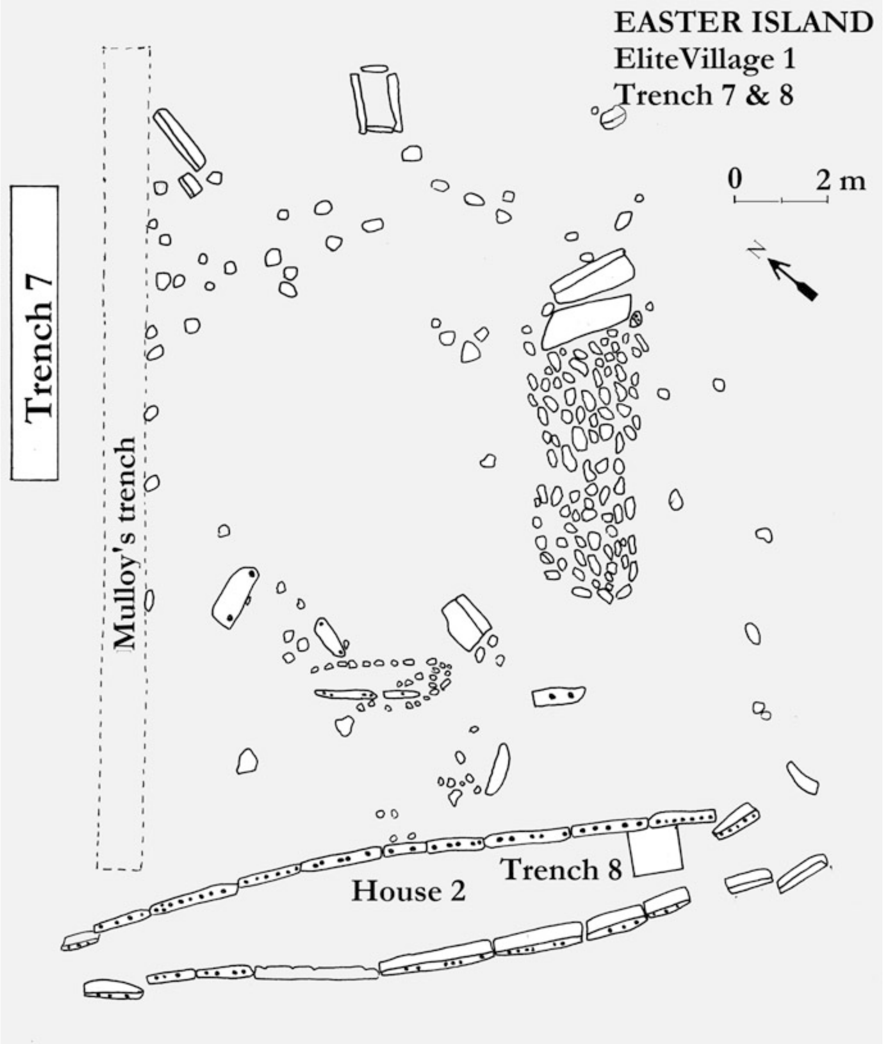

Fig. 8.9 (**a**) Map of elite village no. 1 with Trench 7 and 8 from 2002 and Mulloy's trench from 1955 (©Paul Wallin and Helene Martinsson-Wallin). (**b**) Section of Trench 7 from excavations in 2002 (©Paul Wallin and Helene Martinsson-Wallin)

hammer stone. Towards the bottom of the square was a bird bone, a possible human bone, and a shell were found.

Square 6 was placed just on the edge of the slope located down towards the *ahu* structures and the sea. Just under the top soil cultural activities were evidenced by scattered charcoal, obsidian flakes, fish and bird bones and a *poro*. Below this was a 30 × 20 cm diameter and 4 cm thick charcoal lens (*feature 3*). Further down, on top of the uneven bedrock was an earth oven (*umu*) 30 × 50 cm in dimension and

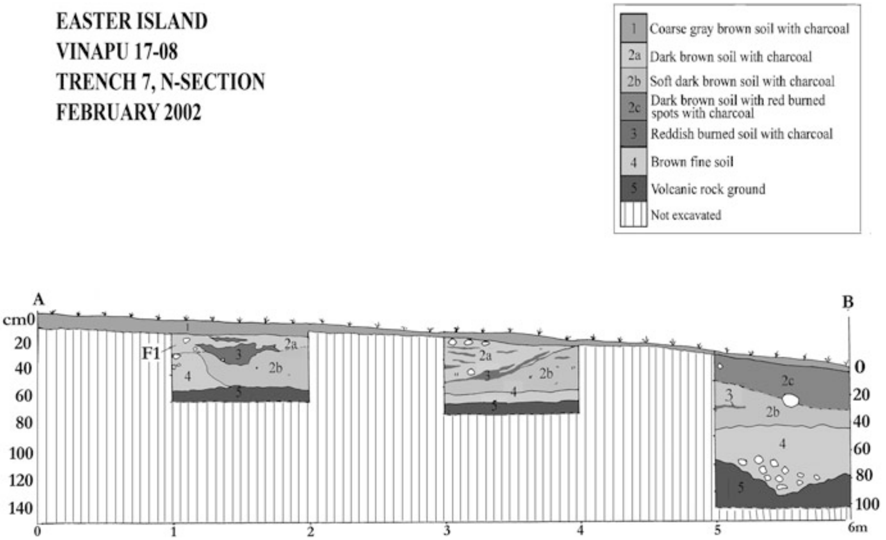

Fig. 8.9 (continued)

15 cm deep. Here there were additional obsidian flakes and tools as well and bones of fish, chicken and shell (see Fig. 8.9b).

4.4.2 Trench 8

To understand the stratigraphy and activities inside the *hare paeŋa* (house no. 2) and compare it to the stratigraphy and activities encountered outside of the houses, we excavated an 1 × 1 m test unit (no. 8, see Fig. 8.9). Under a thin layer of vegetation and topsoil was the hard-packed floor of volcanic soil, which was about 18 cm in thickness and flecked with scattered charcoal. In the top part of this layer was a rounded area with scattered charcoal 20 × 20 cm in diameter and 2 cm thick. At this level there was an abundance of obsidian flakes and a few obsidian tools, a hammer stone, and fragments of human bone (a long bone and a cranial bone). At the bottom of the layer was a ca. 40 × 40 cm area of *poro* and a small slab of basalt (*keh'o*). Under the floor was a layer of finer brown soil with some scattered charcoal and obsidian flakes. The remains seemed recent but the obsidian flakes returned dates of BP 777 ± 66 (AD 1225), 567 ± 57 (AD 1435), 482 ± 52 (AD 1520), 341 ± 44 (AD 1661) (Table 8.4) and the results are inconclusive.

4.5 Additional Excavations

Three additional trenches (no. 5, 9, 10) were located in various parts in the Vinapū study area. On the inland side of *ahu* Tahiri, which is likely to have been part of the original plaza but now near the car park, we excavated a 1 × 2 m trench (no. 5). Here we encountered surface artefacts of worked basalt, a *poro*, a possible *toki* fragment and flakes of obsidian and basalt. Below this layer was a cultural layer of 45–50 cm in thickness which only displayed a few pieces of charcoal. Further down was a layer that displayed roots molds from palm trees (*Paschalococos disperta*) and holes produced by other trees from planting activity (Fig. 8.10, compare to Trench 1, square 8).

Two test trenches were placed in the areas in between the *ahu* structures and the elite villages. Trench 9 was 150 m north of elite village no. 1 and located on sloping ground. On the surface and in the top soil were obsidian flakes and a few *poro*. The same cultural layer as found in most trenches followed, and it contained a few obsidian flakes. In the bottom of this layer, there were areas with softer soil that were interpreted as root holes. Below this was the original volcanic soil.

Another trench 1 × 2 m in size (no. 10, see Fig. 8.2) was excavated on the hillside ca. 50 m southeast of the isolated tomb. The surface was sloping towards the east in the direction of the *ahu* structures. In the top soil an obsidian core was found. Below this was the same type of stratigraphy and root holes/ planting pits as encountered in many of the other trenches.

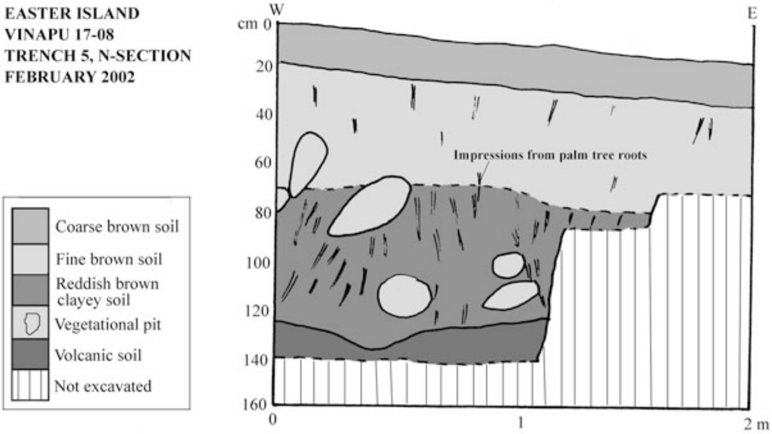

Fig. 8.10 Section of the Trench 5 from excavations in 2002 showing the imprints of root molds from the palm tree *(Paschalococos disperta)* (©Paul Wallin and Helene Martinsson-Wallin)

5 Discussion of the Vinapū Excavations

Mulloy's excavations and restoration programme focused on the ceremonial sites and to some extent the elite village no. 1. His interpretation was that the *ahu* displayed three construction phases. Based on construction details and radiocarbon dates, he suggested that the earliest construction of the *ahu* at Vinapū consisted of platforms of cut stone that served as altars and had an astronomical orientation, but without statues. Subsequently, the structures were transformed to form the bases for statues that were part of an ancestral cult. The masonry was cruder and worked stones from the previous phase were re-used. In this later phase, Mulloy suggests (1961:159): "There was also lack of symmetry in the construction". In the last phase, the structures served as burial sites, and according to Mulloy (1961:160): "a period of decadence, perhaps resulting from internal warfare and abandonment of the practice of working large stone" had taken hold. The chronology of the time relied on radiocarbon dates with the earliest date of "AD 857" from a sample found under the embankment of the plaza of *ahu* no. 2. An Early to Middle phase sample from the crematorium of *ahu* Tahiri dated to "AD 1228". Mulloy further suggested that the Middle period ramp construction at the same *ahu* dated to "AD 1516" and the Late Period is dated to "AD 1837" evidenced by a surface collection on the ramp. The dated samples are presented in Table 8.3.

Mulloy's dated samples have broad ranges and are unidentified wood types and they cannot be used for detailed discussions about temporal matters. However, Mulloy and his team's stratigraphic observations and details of monument building are of importance to the interpretation. It is quite clear that Mulloy, contrary to Heyerdahl (1961), is not advocating for the interpretation that two different and non-related cultural groups have been involved in the changes seen in the monument but that these changes depended on internal development (Mulloy 1961:160; Mulloy and Figueroa 1978). Mulloy is not specific on the temporal relationship between the *ahu* structures but suggested a long abandonment of the structures between the Early and the Middle phases, especially at *ahu* no. 2.

Since the time of Mulloy's investigations, the chronological framework for colonisation on Rapa Nui and the construction of a*hu* sites has been refined and the cultural historical approaches partly abandoned (Skjølsvold 1994; Wallin et al. 2010; Wilmshurst et al. 2011; Hunt and Lipo 2006; Lipo and Hunt 2016; Martinsson-Wallin et al. 2013; DiNapoli et al. 2020). In our re-excavation at Vinapū, we were not granted permission to do investigations at the *ahu* sites, or its related structures, other than the embankment of the plaza. Due to evidence from the excavation, we have concluded that the activity under the embankment is much younger than previously suggested by Mulloy and *two new dates on nutshell from two contexts establish dates of AD 1304–1437 and AD 1303–1442* (2σ). Another cultural activity in the top of what appears to the same cultural layer as the latter, but further upslope, gave a date of *AD 1503–1808* (2σ). The sample dated by Skjølsvold and Figueroa in the crematoria of *ahu* no. 2 give a range to *AD 1268–1635* (2 σ) and the bones from the crematoria at *ahu* Tahiri returned a date range of *AD 961–1643*

(2 σ) (see Table 8.3). The two latter dates have broad ranges, and the date from the crematoria of *ahu* Tahiri cannot be used in the discussion. An additional date by Mulloy is from the ramp of *ahu* Tahiri, which he interpreted as in between the Early and Middle Period, gave a range of *AD 1321–1673* (2 σ).

One feature that is briefly discussed by Mulloy as an Early Period feature, and subsequently noticed by Martinsson-Wallin (1994), is the pavement found exposed by Mulloy's excavation on the inland side of *ahu* no. 2, below the north wing (see Heyerdahl and Ferdon 1961, Plate 11a and Fig. 133). It is slightly offset and oriented in another direction than the *ahu* and the plaza outlined by the embankment. It is likely part of an earlier structure at the site. Martinsson-Wallin (1994) suggests that from construction details and relational statistical data that wings and ramps are added to the monuments over time. Based on former excavations and re-assessments of the Rapa Nui chronology, it is suggested that this pavement at *ahu* no. 2 could have been part of an earlier Polynesian style ritual site. An early site could feature a level pavement associated with uprights, of which some could be seen in the seaside wall of *ahu* no. 2 (compare this discussion to Wallin and Martinsson-Wallin in this volume).

Another important finding in our re-excavation is that many of the trenches displayed root imprints of the large palm tree and traces of planting pits or roots of other types of trees and bushes. These remains in association with charcoal lenses and scattered charcoal in the cultural layer are probably evidence of slash and burn activities used to clear land. Mulloy also mentions findings imprints of roots belonging to palm trees. Delhon and Orliac (2010) and Meith and Bork (2010) have discussed the occurrence of the palm trees and the latter estimate that the island originally was densely covered with giant palm trees when the first people arrived on the island sometime in the twelfth to thirteenth century. Delhon and Orliac (2010:108) suggest that the palm trees were common in Rapa Nui at least until the fourteenth century, which also are partly confirmed by recent research by Rull (2020). However, Rull's results of samples from the three crater lakes show a complex and quite localised picture of the deforestation pattern (2020:136). Vinapū is located closest to Rano Kao, and according to Rull (2020:136) had an abundance of palm trees prior to human settlement but was negatively affected by a drought around AD 1000–1100 and then by anthropogenic fires around AD 1100–1200 and AD 1300–1400.

An additional observation is that the *ahu* structures probably were used as burial sites in connection with the destruction and pulling down of the statues and the statues seem to be intentionally buried and hidden just as the humans remains (Ayres et al. 2014).

When it concerns the investigation at the elite houses of village remains no. 1 the excavation did not reveal different phases of habitation at this site. The *mata'a* found in the bottom of the excavation could indicate a late prehistoric use phase but recent research on dating of *mata'a* in the vicinity of Akahanga (Stevenson and Williams 2018) point to that *mata'a* have a long use phase which had one peak around AD 1400 and another extensive peak around AD 1700–1800. Later activities show destruction and dismantling of the houses that could have occurred after European contact as material culture from this period was found at the site.

Based on Mulloy's investigation, our re-investigation, and the collective research data from other scholars, as well as ethnohistoric accounts, I suggest the following interpretation of how the Vinapū area may have been used by people for various activities over time.

5.1 Early Vinapū

Dated samples from short-lived species in combination with stratigraphic evidences shows that an abundance of palm trees and other vegetation were growing in the Vinapū area prior to *AD 1304–1437*. Furthermore, the cultivation of yam is possible among the palm trees. Based on Mulloy's excavations, and the pavement he found in front of the north wing, together with uprights that later were re-used in the rear wall of *ahu* no. 2, it is hypothesised that *ahu* no. 2 belonged to an early Polynesian style ritual site (pavement with uprights) placed at Vinapū prior to the date mentioned above. New investigations at the *ahu* could test this hypothesis.

5.2 Ahu/moai Construction and Use (AD 1300–1864)

5.2.1 AD 1300–1400

During this time frame, there was a rapid expansion of monument building in Rapa Nui. See for example the re-assessment of radiocarbon dates taken from *ahu* by DiNapoli et al. (2020), which use Bayesians statistics on an extensive series of dated samples from previous researcher's archaeological investigations and interpretations. Based on Mulloy's observations, it is indicated that the initial focus was placed on elaborate platform stonework and smaller statues positioned on a level pavement in front of the *ahu* as seen for example at *ahu* Nau Nau I at Anakena (Skjølsvold 1994; Martinsson-Wallin 1994; Wallin et al. 2010). Our excavation and the results of Rull's research on the deforestation (2020) indicated a large-scale clearing of palm trees, probably by slash and burning, started in the area during this period. It is suggested this was carried out to create farmland for the imported crop sweet potato that became a staple food for a growing population and as fuel for the extensive expansion of elaborate stonework (Wallin et al. 2005).

Later in this period, the elaborate stonework masonry changed from a focus of the rear wall façade to adding elaborate *moai*, ramp, wings and front wall stone masonry. Earlier small statues and uprights of various material were mutilated and/or incorporated and re-used into the *ahu* structures (Martinsson-Wallin 2000). For example at Vinapū a smaller statue of Rano Raraku tuff is present on the seaward side of *ahu* Tahiri and the red "cremation" stone found in front of *ahu* no. 2 could be such an early statue. A hypothesis is that these changes are tied to power relations, an increasing stratification and struggle over resources. A possible driving force could be a growing population and/or external contacts and climate variation. For example recent DNA studies by Ioannidis et al. (2020) show that old SA genes are present in the Rapanui population but what this entails is not clear. However, Martinsson-Wallin (1994, 2000) and Martinsson-Wallin et al. (2013) have set forward the hypothesis, based on comparative archaeological research, datings and ethnohistory, of two different early migrations to Rapa Nui. The introduction of the sweet potato, the stone technology and an early "*huri moai*" event (mutilation and incorporation of early small statues in *ahu* structures) could be expressions of two different early waves of colonists. Other factors that could have contributed to turmoil within the society is unsustainable population growth in combination with climate variation (Lima et al. 2020; Rull 2020), and natural disasters such as tsunami events, like the one that happened at Tongariki in 1960. Effects of earthquakes that caused damage to the *ahu* structures have also been discussed but not proven. However, natural disasters in the form of a tsunami are not likely to have affected the *ahu* structures at Vinapū, considering the elevation of the site.

5.2.2 AD 1400–1600

This time period is a continuation of site utilisation and the addition of the classic *moai*, ramps paved with *poro*, *pukao*, wings and nicely cut *paeŋa* on the inland side of the platform facing. At some *ahu*, (especially on the South coast see Martinsson-Wallin 1994:106) the *paeŋa* were dressed with read scoria lintels, but there are no indications of this occurring at the Vinapū *ahu*. A radiocarbon date by Mulloy from a sample in the ramp of *ahu* Tahiri could point to activities during this time period but since the sample is not identified as short-lived, and has a broad dating range, this date is very uncertain. However, a sample of nutshell from a simple hearth, in association with obsidian and basalt tools, in our excavated Trench 11 show activities in the Vinapū area during this time.

5.2.3 AD 1600–1722

This is a period of continuous use with additions and alterations to the ceremonial sites. The elite houses (*hare paeŋa*) were probably initiated early on in this period. These type of structures with nicely cut foundation stones can be interpreted as evidence for the development of an increased hierarchical society and competition between decent groups. A competition over resources and focus on materialised ideologies probably sparked power struggles and the development of a more stratified society. Our re-excavation of the *hare paeŋa* houses at Vinapū recovered a *mata'a* in the bottom of the excavation at village no. 1. At Vinapū, Mulloy collected around 400 *mata'a* on the surface of the area. They are likely to have developed as a multi-purpose domestic tool (Kononenko et al. 2019) but probably functioned as a lethal weapon as well. The invention of *mata'a* could have been well-prior to the arrival of Roggeveen in 1722 but the increasing manufacture and use could have been a result of the turmoil in connection to the Dutch's disastrous visit in 1722 and later European contacts (see Stevenson and Williams 2018). Research in the statue quarries by Skjølsvold (1961) and Sherwood et al. (2019) that focuses on the decline and transformation of the quarries at Rano Raraku from a manufacturing site to a ritual and agricultural locality probably pre-date the Dutch arrival. Statues seems to stand on their platforms when Roggeveen arrives in 1722, but the arrival of outsiders had a disastrous effect on the society. Several Rapanui were killed by the Dutch. The account from Roggeveen (1722) and Behrens indicate that the Rapanui had hens, nuts (probably some large palm trees were still standing), sugar cane, yam (which was identified by the workers in our excavation at Vinapū), as well as, sweet potatoes and bananas.

5.2.4 AD 1722–1864

This is a period of a growing number of external contacts. The Rapanui experienced several slave raids and colonialist intrusions, which made society unstable and brought diseases such as smallpox to the island. The statues were pulled down but not all at once and the monuments were used as burial grounds and were covered over by stones (see Ayres et al. 2014 and Cauwe this volume). At Vinapū, there are records from Cook's visit in 1774 that three statues had been pulled down and four still were standing at *ahu* Tahiri. When Lisiansky called at the island in 1804, there were only three remaining statues standing at Vinapū and in 1816 only two remained in an upright position. It is likely that the statues and monuments still had importance to the Rapanui but a lot of re-arranging, re-using and destruction is indicated. It is furthermore likely that a conscious choice of "hiding" and "burying" the statues as well burying people in the destroyed monuments was occurring (Ayres et al. 2014). The elite villages at Vinapū and elsewhere started to be dismantled during this time and *paeŋa* from the house foundations were re-used in various ways, which is clearly seen in *ahu* no. 2. Fifty years later, in 1864, when the missionaries arrived in Rapa Nui all of the statues had been pulled down at Vinapū and elsewhere on Rapa Nui. According to the early missionaries, the *'Ōroŋo* festival and the *Tangata Manu* and *MakeMake* god were more important to the Rapanui than the *ahu*-structures but it is likely that the *ahu* structures at Vinapū and elsewhere were still used as a place for the dead.

Acknowledgments I am grateful for the skilled assistance of foreman Sr. Rafael Rapu Haoa and workers Benjamin Rapu Haoa, Ventura Tuki Hotus and Francisco G. Haoa Pakomio in the 2002 excavation at Vinapū. A Rapanui student of anthropology Sra. Susana Nahoe, was also involved and trained in excavation methods. In addition, Susana assisted me in the laboratory work at the Museum. I am also grateful to Sonia Haoa-Cardinali for kind assistance with various practical matters and discussions of the Rapa Nui past. Furthermore, even though we never met, I want to express my fullest respect for William Mulloy and his detailed report of the excavations at Vinapū and for his subsequent research and restoration work in Rapa Nui. Imperialism and colonial history

have severely coloured and affected the Rapanui in many negative and devastating ways during the past 300 years. This includes the use and discussion of the past of Rapa Nui by outsiders but I hope that my and other outsiders' pursuit of the past using archaeological research, is and will be, for the benefit to the people living on the island where people have left "no stone unturned".

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Chapter 9
Undelivered Moai or Unidentified Monument?

Nicolas Cauwe and Morgan De Dapper

1 Introduction

In 1919, Katherine Routledge published the first interpretation to account for *moai* scattered on the landscape lying far away from any architecture. Her hypothesis was twofold. She postulated that some of them probably had adorned the paths that could carry large statues to their final destination, while others seemed to her to have been abandoned during transport (Routledge 1919: 194–196). In conducting excavations in the vicinity of the statues she found nothing around them, except that one was set up within an excavated pit (Routledge 1919: 196). She also took an interest in the runnels created by rainwater runoff located on the back of the statues (Routledge 1919: 195). She suggested that a portion of the images was upright for a long time and that other statues were prone without any obvious reason for their location, except abandonment during their transfer.

After this initial work, few studies were devoted to this phenomenon of isolated statues, except in 1986, when the Czech engineer Pavel Pavel experimented with

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_9

the moving of *moai* in a vertical position. This research was conducted with Thor Heyerdahl and Arne Skjølsvold, and on this occasion, an excavation was made in the vicinity of an isolated *moai*. A small platform was found, confirming the thesis of Routledge that some statues were erected along the roads (Heyerdahl et al. 1989). In the 1990s and 2000s, following the recognition of profound landscape changes caused by deforestation, a collapse scenario was suggested that included intertribal warfare, struggles for survival, destruction of *ahu* platforms and abandonment of the statue quarries. In such a framework of collapse, the single statues, laying on their belly or on their back, were interpreted as abandoned *moai* in which transport was suddenly disrupted by hostilities originating from the 'ecological crash' (Bahn and Flenley 1992, 2011; Flenley and Bahn 2002; Diamond 2005). More recently, a new research effort by Lipo et al. (2012) embraced the same principle of statue abandonment during their transport and came to Pavel Pavel's conclusion that the *moai* could 'walk'. This seems to solve the question of transport technics but not the other historical events surrounding these statues.

Our goal in this chapter is to present a comprehensive analysis of these sculptural remains, for which an inventory has been published (Cauwe and De Dapper 2015) and two recent studies produced (Cauwe and De Dapper 2019; Hamilton 2013). In previous works, Routledge recorded 56 isolated *moai* (Routledge 1919: 194–199) and Carl Lipo and his colleagues noted 61 statues (Lipo et al. 2012). There are many questions about the attributes of these statues, their creation and the context in which we find them. Do all of these statues share the same archaeological and geomorphological conditions? Are they all carved from Rano Raraku tuff? What is the reality of the roads on which they are supposed to rest? Why did the islanders move so many statues at the same time? Why did they place the majority of the *moai* only in the vicinity of the quarries and not all along the roads? Therefore, in 2010 and 2011, within the context of the Belgian Expedition to Easter Island, a database was built to list all single statues still visible on Rapa Nui (research organised with the support and the financing of the Federal Public Planning Service Science Policy (BELSPO), project MO38/18). We have found 67 *moai*, but it is possible that some statues were partially destroyed or removed over time, and some others are now on private properties and are difficult to access. Nevertheless, we can assume that the sample considered here is representative of the phenomenon.

2 Historical Testimonies

With respect to the isolated statues, the main historical data we have available to us is the testimony of William Wale, a lieutenant of Captain James Cook during his second voyage around the globe (1772–1775). He states:

> This side of the Island is full of those Colossean [sic] Statues which I have mentioned so often, some placed in Groups on platforms of Masonry others single and without any being fixed only in the Earth, and that not deep; these latter are in general much larger than the others. I measured one which was fallen down & found it very near 27 feet long & upwards

> of 8 feet over the breast, or shoulders and yet this appeared considerably short of this size of one which dined near: its shade at a little past 2 oClock being sufficient to shelter all our party, consisting of near 30 persons from the Rays of the sun (Beaglehole 1969: 825).

This quotation from the report of William Wale takes place during his account of a party on the southeast sector of the island. We cannot know exactly what he saw, but in this sector of Rapa Nui, there are images associated with platforms, *moai* erected on the south slopes of Rano Raraku and probably isolated *moai*. Wale's description of single *moai* corresponds to the statues we can observe today laying along the ancient transport paths, and as noted centuries earlier, these statues have more impressive dimensions than those associated with *ahu* platforms. According to Wale, in the eighteenth century, a portion of these *moai* was upright and placed on *ahu*.

No other explorer of the eighteenth or nineteenth century noted the presence of isolated statues or considered them important enough to record. Only William Thomson gave a short mention of a single *moai*:

> Scattered over the plains extending towards Vaihu are a large number of images, all lying face dounward. The indications are that they were being removed to their respective platforms when the work suddenly arrested. These heavy weights were evidently moved by main strenght, but why they were dragged over ground face downward instead of upon their back, thus protecting their features, is a mystery yet unsolved. One statue in a group of three is that of a female; the face and breast is covered with lichen, which at a sort distance gives it the appearance of being whitewashed (Thomson 1889: 496).

This testimony marks the starting point of the hypothesis that all of the single *moai* scattered between Rano Raraku and Vaihu were abandoned during their transportation. But the most interesting detail of Thomson's account is that all of the observed isolated images were laying down at the end of the nineteenth century. If we give credibility to his report or to the one of WilliamWale, only a portion of single *moai* were yet lying down at the end of the eighteenth century, but all of them were in a prone position by the middle of the next one.

Katherine Routledge was the first to propose the hypothesis of *moai* verticality. This was generated by the important observation that eroded runnels created by rainwater runoff were on the statues and that they formed when the statue was in a vertical position (Routledge 1919: 195). Thus, all of the historical testimonies agree. In the eighteenth century, some *moai* were perhaps still upright in the southern plain of Easter Island, but some decades later, all of them were laying down. Routledge also recorded that the larger part of the set of images was unbroken and only some of them would have fallen by accident, natural process or violence (Routledge 1919: 195).

3 The Archaeological Data

3.1 Categories of Single Statues

The 67 *moai* recorded during our surveys can be placed into six groups:

1. The most important group (46 *moai*) includes the statues laying along what is usually called the '*camino de los moai*' (road of images). Except for four of them, all are carved in Rano Raraku tuff.
2. Six *moai* are partially buried in front of two *ahu* (five at Ahu Hanga Poukura and one at Ahu Ura Uranga te Mahina). Their story seems to be different from that of the statues along the ancient roads.
3. Two *moai* are very small (only 1 m high) with a distinct round head and without facial details. They form a special type unrelated to the images on *ahu* and from Rano Raraku.
4. On the northern slope of Rano Kau, an outcrop of basalt is carved in the shape of a *moai*. The proportions are unusual and unique to the island.
5. One image is inside a small cave that opens on the eastern flank of Vai a Heva (Poike). This archaeological context has no significant relationship to the problem of *moai* transport on the open landscape.
6. Finally, 12 *moai* were probably moved in recent times. Those at Hotuiti Bay lie fragmented and their poor state may be tied to a natural breakage caused by a tidal wave perhaps. Another one is lying in front of *Ahu* Tongariki, a monument destroyed by a modern tidal wave in1960 and recently restored. A *moai* was also re-erected near *Ahu* Tongariki after its use for an experimental moving of a *moai* by Pavel (1988, *Idem* 1995). A statue also lies in front of the *Ahu* Runga Va'e where it was recently consolidated within a retaining wall. The statue was moved during this conservation work (Rafael Rapu comm. Pers.). In 2000, some young Islanders have re-erected a *moai* close to the Vaihu Bay (*Rapa Nui Journal* 14/42000:120). The face of the *moai* laying near *Ahu* Riata (Hanga Piko) is 'repaired' with cement. Finally, there are tree *moai* re-erected at Hanga Roa (one at the Hotu Matua Plaza near the *caleta*, and two inside the garden of the Museum Sebastian Englert).

Only the first category of *moai*, those scattered along the ancient roads, can support an analysis. The recently moved statues can no longer be considered and other categories form special cases. The 46 *moai* covered by our analysis are now laying on their back (16 *moai*) (Fig. 9.1a) or on their face (30 *moai*) (Fig. 9.1b). This situation has long allowed persons to claim that the statues came from the Rano Raraku quarry and were transported standing on wooden sleds. The unexpected event during their transport caused their fall on the ground, in one or other direction and led to their abandonment.

Fig. 9.1 (**a**, **b**) Intact or broken images along the ancient roads (total: 46 items)

3.2 *Stade of Conservation of the 46 Moai Scattered Along the Paths*

Lipo et al. (2012) mention that 37% of broken *moai* occur along the old paths. They conclude from the presence of broken *moai* that all of the images scattered along the paths did fall while they were being moved. Actually, only two statues were probably broken before or during their being placed on their back because of the scattering of their fragments. These are two small *moai* of red scoria abandoned

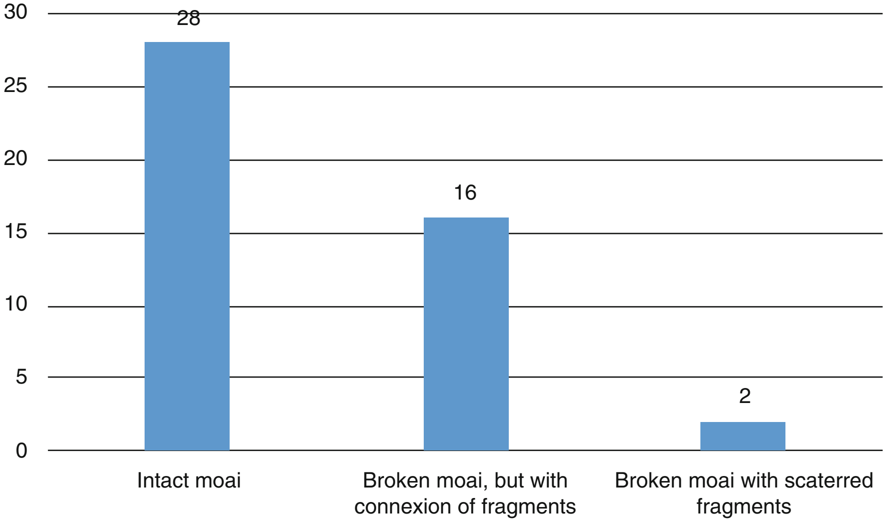

Fig. 9.2 More than half of the images lying along the roads are intact (**a**), the rest are broken, but without dispersion of their fragments (**b**)

along the ‘North-Western road’ of Routledge (1919: Fig. 74) or at the end of the ‘road B’ of Lipo and Hunt (2005).

For the remainder, 28 statues are undamaged, while 16 *moai* are broken, but their fragments remain adjacent to one another, and two are broken with scattered fragments (Fig. 9.2). Lipo and Hunt do not make any distinction between the two categories of broken *moai*, those with adjacent parts and those with scattered fragments. However, the reasons for both situations cannot be the same. The only explanations for the adjacent fragments are a deliberate reconstruction of the statues after their accidental or intentional toppling, or that breaks occurred later as a result of stress or bending when the images were already lying down. In this, case the tuff is not strong and compact enough to withstand such stresses.

The biggest *moai* along a path, close to the northern face of Rano Raraku, has its face partially fragmented, but the nose and other fragments were replaced back to their original position, certainly before the Mana Expedition of Katherine Routledge (Routledge 1919: 195). We can observe the same process of reconstruction of the face of other images. In addition, the inside breaks of nine *moai* have intentionally positioned small blocks. This placement is an old action since the slow-growing lichens form a continuous veneer on both sides of the image fragments and also on small stones put inside the breaks. Maybe, the insertion of small stones can be

Fig. 9.3 An example of a 'repaired' statue (small stones have been placed inside the break). The development of lichens inside the break and on the small stones indicate the antiquity of this 'healing' of the *moai*

considered as a symbolic repair or a 'healing' (Fig. 9.3). But there are also *moai* undoubtedly broken by overhang stresses without rebuilding or repair (Fig. 9.1b). We do not observe any trace of a voluntary mechanical action on these last images (intended shocks to the statue). Routledge also spoke about 'cleavage' and 'partial fall' (Routledge 1919: Fig. 76).

3.3 Pavements, Chocking Stones and Pits

Overall, very few statues support the accident hypothesis. If the *moai* along the roads were abandoned during their transport, they would have had to be moved in a horizontal position, sometimes on their belly, sometimes on their back. If this was not the case and they were transported in a vertical position, then they were toppled with care. It is significant that 30 of them (65%) are maintained in horizontal position with the help of chocking stones. The reason for this is not clear but it is undoubtedly human work. The statues are lying on stone pavements which is evidence for their intentional positioning (Fig. 9.4a, b).

Fig. 9.4 (**a**, **b**) Images of *moai* along the road lying on stone pavements

Furthermore, four isolated *moai* scattered along the paths are partially buried inside shallow pits (Fig. 9.5) and four other cover graves (Fig. 9.6). Whatever the story of these statues was, these circumstances indicate that their current position is the result of intentional acts and totally unrelated to failed transport. Stone pavements, burials or associated pits are not features that are usually associated with the transportation process of colossal statues.

Fig. 9.5 An isolated *moai* partially buried in a pit

Fig. 9.6 An isolated *moai* covering a burial. We do not know if the grave is contemporaneous with the statue, but the latter is lying on a stone pavement on which were buried one or two bodies. One can be sure the pavement is older than the burial and the laying down of the image

3.4 Bevelled Eyes and Rock Art

The orientation of the *moai* along the roads is also interesting whether they are lying on their back or their face. If we re-erect all of these statues, they would have their backs oriented to Rano Raraku, the quarry from where they were made then extracted. This particularity was recorded by Routledge (1919). This preferred orientation cannot be a result of chance and some will argue that it is further evidence of the moving of upright statues with their faces visible to the approaching visitors and their backs indicating their origin (Lipo et al. 2012).

However, the archaeological data allow us to generate other hypotheses. It is very exciting to note that 38 *moai* (83%) have their eyes carved only as bevelled indentations, similar to the images of Rano Raraku, and not with sockets as found on the statues erected on *ahu*. The traditional hypothesis is that the bevels were carved before the transport process and later converted to more rounded eyes. This seems to be a correct interpretation since, except for a few *moai* as those of Ahu Nau Nau, the *moai* of the *ahu* have eye sockets without a trace of primitive bevels. Another interesting observation is that a large number of the *moai* from Rano Raraku, or the ones laying along the ancient roads, have bevels so deep that it is no longer possible to carve rounded eye sockets (Fig. 9.7a, b). This would indicate they were not intended to undergo the final transformation.

We, therefore, hypothesise there are two categories of statues. There are *moai* belonging only to the ancient roads and those erected on *ahu*, with a large proportion of the first type not able to support a transformation to the second. The physical sizes of the two types are also discordant where the *moai* from the roads are on average longer and wider than those of the platforms (Fig. 9.8). Jo Anne Van Tilburg has built a computerised database of 887 *moai*, including the 387 statues from Rano Raraku where 134 of them were suitable for taking measurements (Van Tilburg 1994). The result of this research is the recognition of four groups or size categories, with the biggest *moai* being those preserved on the slopes of Rano Raraku and along the roads. Therefore, it seems that the *moai* never associated with an *ahu* belongs to a special category (Van Tilburg 1994). Their average height is 6.2 m (Fig. 9.8) compared to 4.05 m for those *moai* moved to an *ahu* (Van Tilburg 1994). Faced with this observation, it is not so easy to accept the idea that the statues along the paths were destined to arrive at an *ahu*.

Finally, we observed the presence of engravings on five *moai* along the roads. The *rei miro* is the main theme (three cases; Fig. 9.9a) and one statue has on its

Fig. 9.7 (**a**, **b**) *Moai* with bevelled eyes (**a**: along an old road; **b**: a large statue on the southern slope of Rano Raraku). Often the bevels are too deep to carve eye sockets

left cheek the face of Makemake (Fig. 9.9b). On two other *moai* we can only see some poorly defined engraved lines. All of the figurative patterns were drawn after the statues were in a prone position. Indeed, one *rei miro* is engraved on the base of a *moai* and all other markings are in accessible places. It is our interpretation that some *moai* along the roads have experienced a symbolic re-use after their placement in horizontal position.

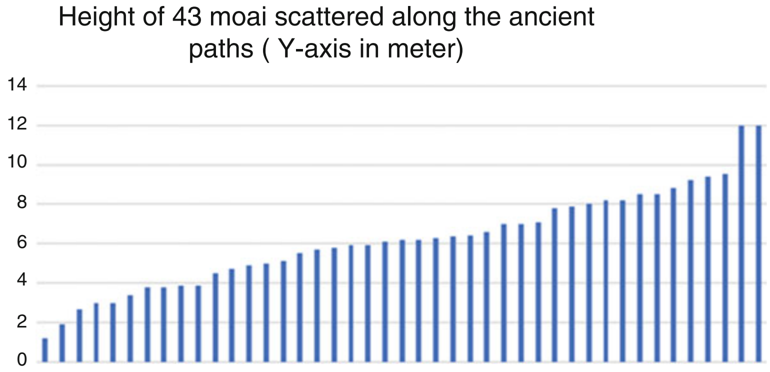

Fig. 9.8 A bar graph showing the height of the statues along the roads (43 items). 33 of them are more than 4 m in height, including 11 exceeding 8 m (measurements made by the authors). The average is 6.2 m for statues along the road compared to 4.05 m for the images installed on *ahu* (refer to Van Tilburg 1994: 23 for the dimensions of *moai* on *ahu*)

4 A New Geomorphological Approach

This brief analysis of the statues along the *camino de los moai* shows that they had a more complicated history than a simple abandonment during their transport and a geomorphological approach will help decipher the life history of these images.

4.1 Geomorphological Processes Acting on the Statues

The vast majority of the statues in our data set are carved from the Rano Raraku palagonite tuff (Gonzales-Ferran et al. 2004; Fig. 9.10). This tuff, resulting from the interaction between water and the basalt melt, can be considered a sedimentary rock consisting of alternating horizontally bedded coarse and fine pyroclastic material with a certain strike and dip. It stands for this reason that such a sedimentary structure is prone to differential erosion by water runoff with the layers formed by finer clastics being more erodible than those with coarser ones. As a result, when exposed for a considerable time to rainfall, which was certainly the case on Easter Island, the original humanly smooth surface of the *moai* will be transformed into a rough eroded surface marked by a distinct network of runnels. The runnel pattern will depend on two variables which include the way the statue was cut from the tuff and its position when attacked by rainfall.

The pattern of the sedimentary layering on the statues will depend on the spatial position of its structural axes (x, y, z) with regard to that (strike, dip) of the tuff. To assess this effect a simulation was done using a digital 3D model. It stands to reason that the morphology of the runnel network will also depend on the position of the statue, whether it is standing or laying down, when subjected to differential erosion

Fig. 9.9 (**a**, **b**) Engraved statues (**a**: *moai* with a line of *rei miro* petroglyphs along its right arm; **b**: *moai* with a the face of Makemake on its left cheek)

by rainfall runoff. The effect of the latter will be strikingly different when compared to cutting as the bedding planes of the tuff run more or less along the *y*-axis which is in most cases (Fig. 9.11).

A few examples will illustrate the effect of erosion on upright and horizontally positioned statues. In the case of a *moai* along road ‘E’ (X 0669139; Y 6998022; Fig. 9.12a) the runnel runoff direction will be different depending upon its position. To begin with, the major runnels are along the long axis of the statue and widen consistently towards the base (Fig. 9.12b) and even affect its shape (Fig. 9.12c). In

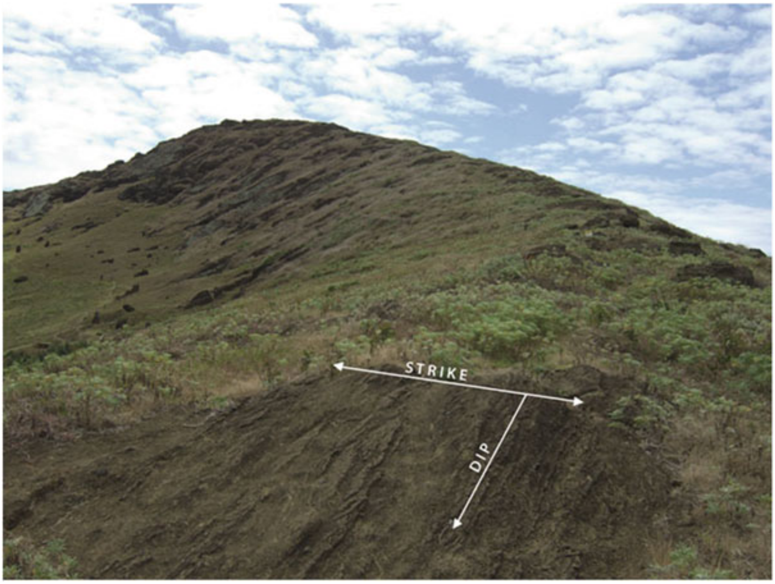

Fig. 9.10 Exposure of palagonite tuff on the inner slope of Rano Raraku

addition, a distinct network of small overflow runnels, superimposed on the major ones, is active in the present day (Fig. 9.12d). The following conclusions can be drawn from these observations: (1) the statue was standing upright for a considerable time; (2) while standing the base was covered; and (3) the length of time for the present prone position was much shorter than that for the upright position. These conclusions are supported by other *moai* that exhibit erosion features that show two opposite runoff directions depending on its history of position (Fig. 9.13a). In a number of cases, the runnels widen towards the base of the statue, and the chin is also affected by deep runnels (Fig. 9.13b–d) which can only be explained if the water was running down from the top of the head of a standing statue.

Another *moai* along road ‘E’ (X 0667176; Y 6997495) lays broken into several large pieces (Fig. 9.14a). As a result, it has two runoff directions, one of which is opposite to the pattern created when it was in a standing position. On the back of the head the runnels widen in the opposite direction of the present runoff and they continue, as if the statue were intact, on the lower back of a second fragment (Fig. 9.14b, c). The fracture plane at the base of the head is only slightly affected by runoff (Fig. 9.14c). Here again, one can conclude the statue was standing upright for a considerable time. The relatively fresh fracture plane points to a recent event where the head may have broken off at the moment the statue was laid down.

Fig. 9.11 Statues with bedding planes of the tuff running more or less along the *y*-axis

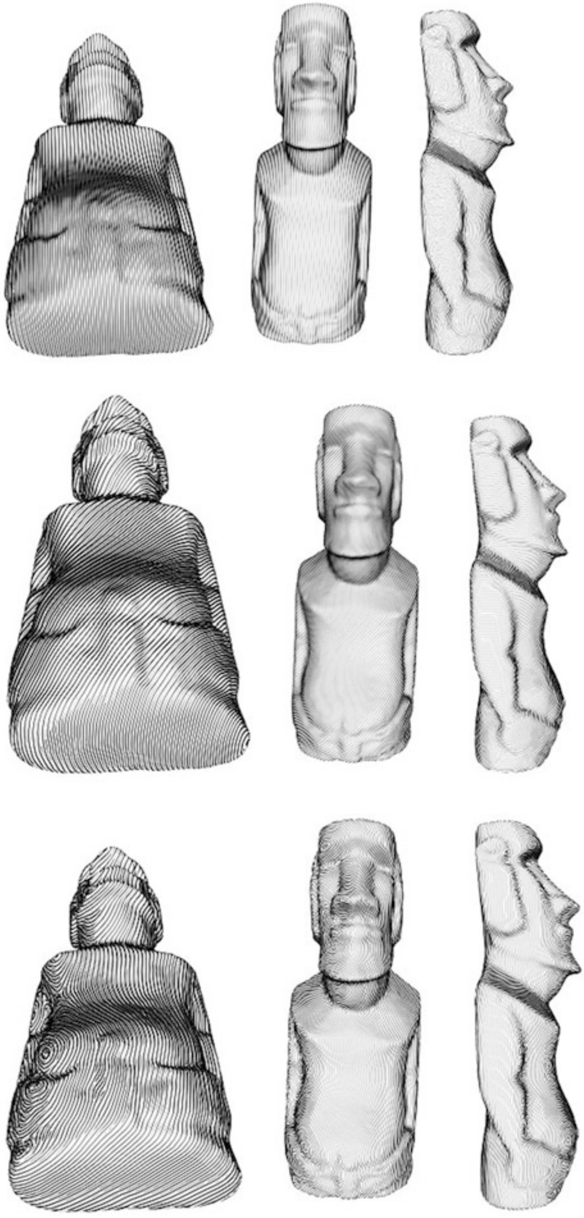

Fig. 9.12 Geomorphologic study of a *moai*. (**a**) Runoff directions are opposite whether in a standing or prone position. (**b**). Runnels widen towards the base; the result of an upright position. (**c**) Runnels affect the base of the statue which was not standing in a pit; the walking stick measures

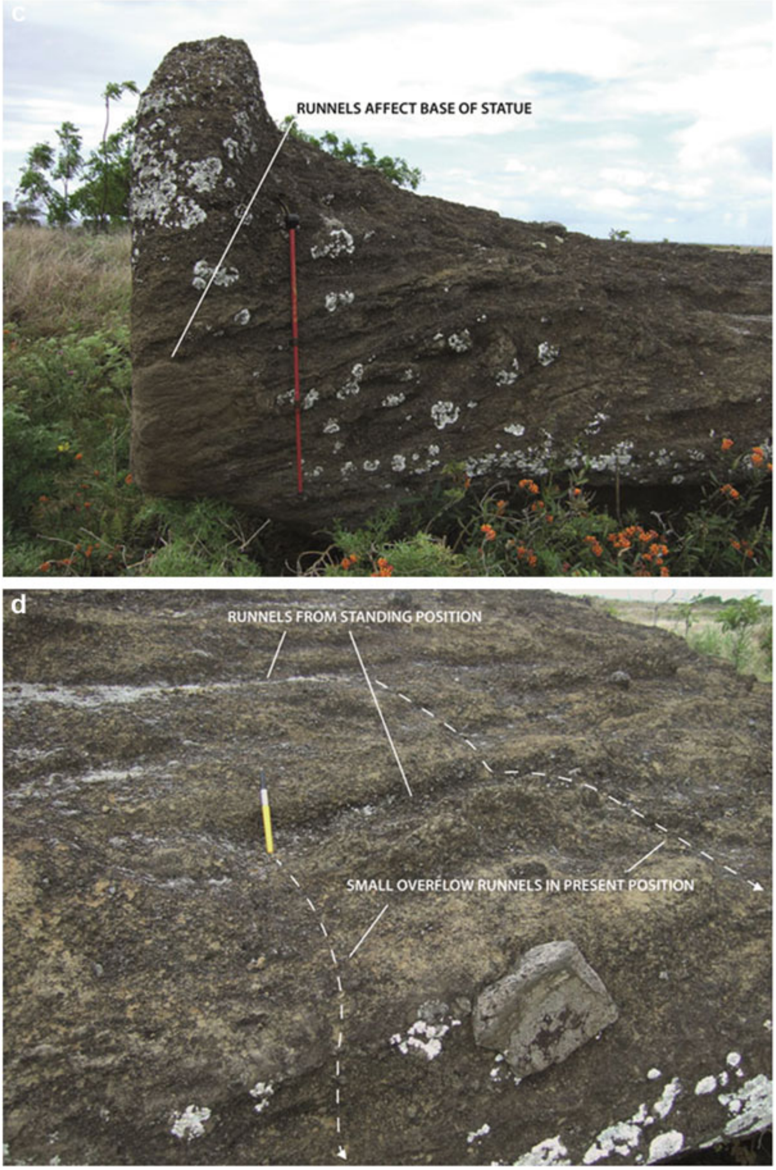

Fig. 9.12 (continued) 1 m. (**d**) Detail of area indicated on (**a**). Small overflow runnels, actively developing in the present-day prone position, are superimposed on a major runnel network developed in the former standing position; the pen is 15 cm long

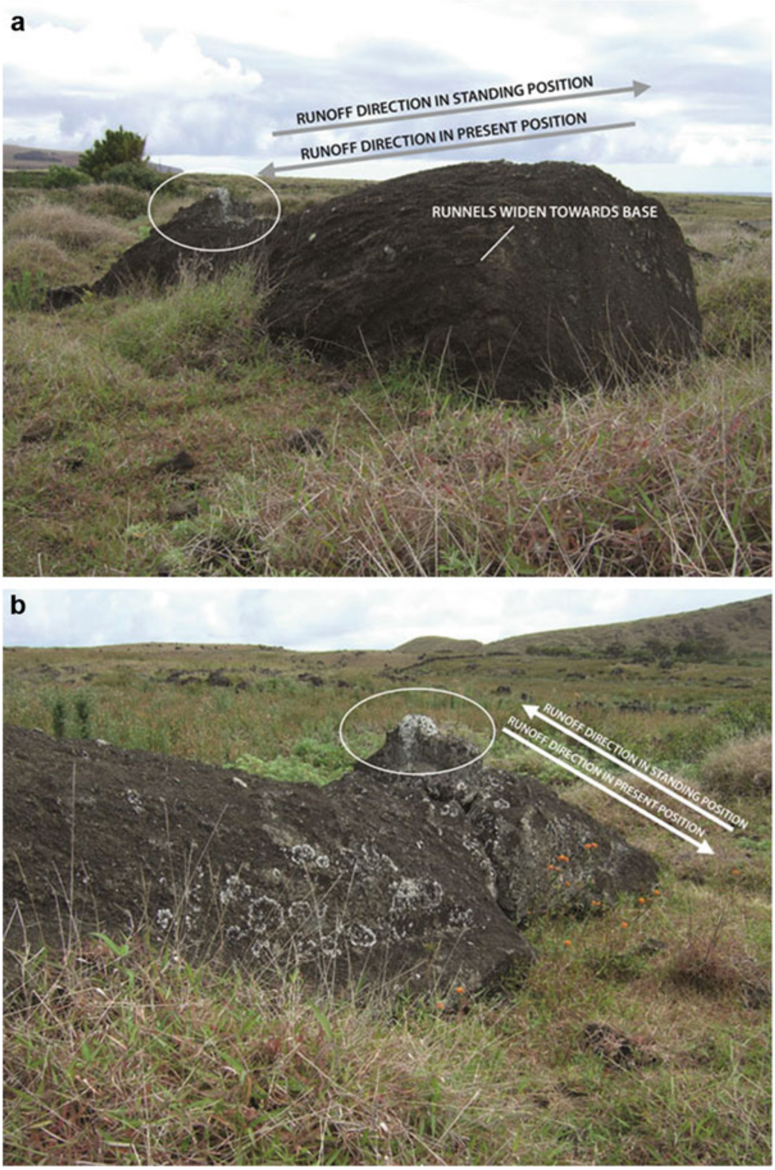

Fig. 9.13 Geomorphologic study of a *moai*. (**a**) The runoff directions are opposite whether in a standing or lying position; runnels widen to the base as a result of a long upright position. (**b**) The head has two opposite runoff directions reflecting the former upright and present position.

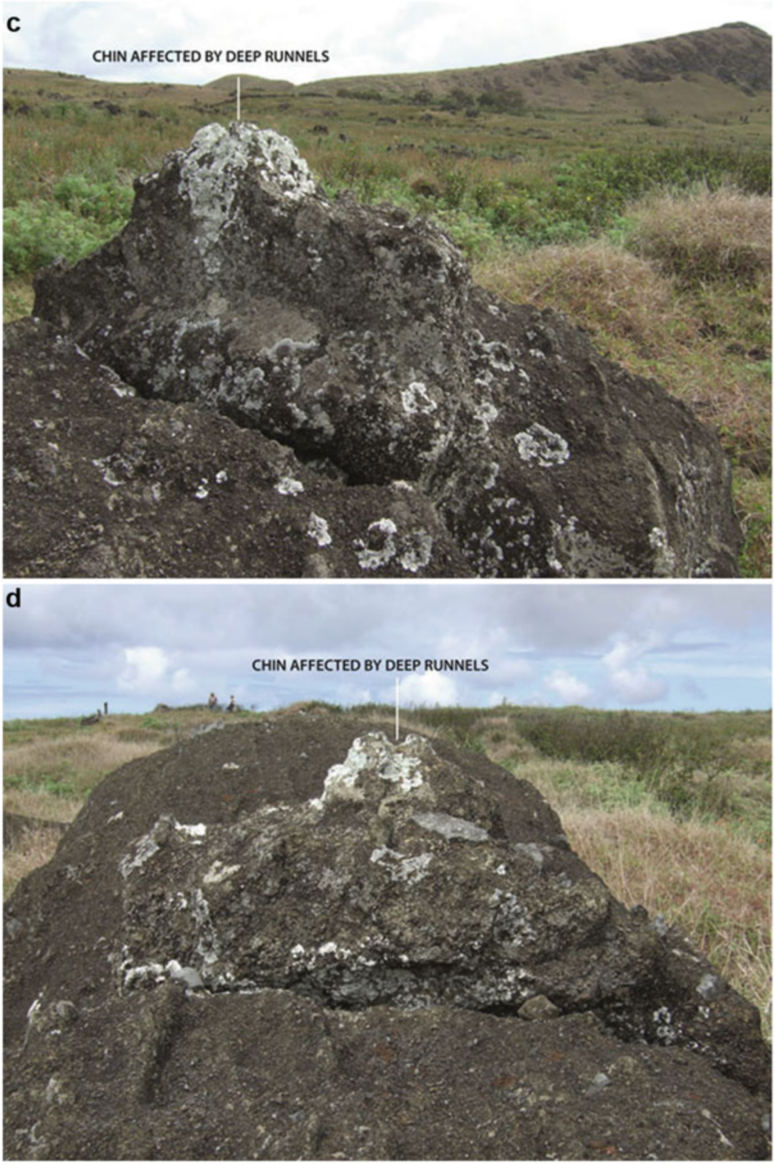

Fig. 9.13 (continued) (**c**, **d**) Details of the head (respectively as seen from the base and from the top of the head) indicated on (**a**) & (**b**). The chin is affected by deep runnels, a phenomenon which can only be explained if the statue was standing upright for a long time

Fig. 9.14 Geomorphologic study of a *moai*. (**a**) The *moai* lays broken in large fragments which have opposite runoff directions different from the unique runoff direction in the upright position. (**b**) Head fragment as seen from the top of the head. Runnels widen in the opposite direction of

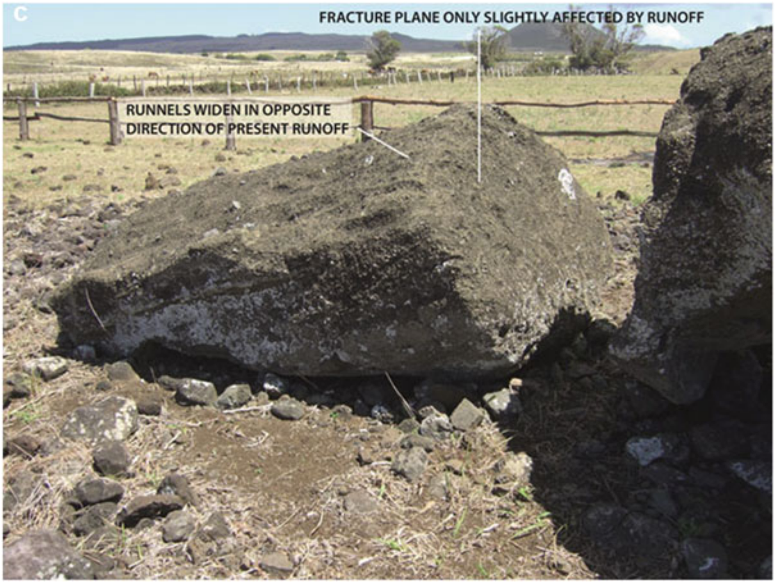

Fig. 9.14 (continued) the present-day runoff and continue along the fragments. Both phenomena are evidence of a long-standing position. (**c**) Head fragment as seen from the side. The fracture plane is only slightly affected by runoff indicating a relatively recent fragmentation that happened when the statue was laid down. However, the segmentation could also have happened after the lay down due to overhang weight or bending

Finally, another *moai* of the road 'E' (X 0659502; Y 6994117) is also broken into large pieces (Fig. 9.15a). It is affected by long runnels which continue over the large and small fragments (Fig. 9.15b) and widen towards the base. Here again, a long-standing position is the most plausible explanation for this runnel pattern.

4.2 Archaeological Consequences

Similar phenomena, as described in the few examples above, are observed on all of the 46 studied statues along the *camino de los moai* and this leads us to the conclusion that they were standing upright for a considerable time.

Fig. 9.15 Geomorphologic study of a *moai*. (**a**) The image is fragmented and has opposite runoff directions whether in a standing or prone position. Runnels continuing over the fragments and widening towards the base is evidence as a result of a long upright position. (**b**) Detail of runnels continuing over connected large and smaller fragments

Six of the *moai* also show runnels ending a few centimetres above their base leaving a narrow unaffected rim. This phenomenon is undoubtedly due to the fact that the statues were erected in shallow pits where the soil protected the statue base region. Pit emplaced statues also tend to a base that is narrower than the rest of the body. On the other hand, statues on which the runnels continue up to the end have very large bases allowing them to stand and remain upright without the support of a pit or another structure (Fig. 9.12a).

On all isolated statues the detailed observation of the runnel network allows us to detect a second generation of runnels actively developing on the present-day prone position statues that is superimposed on a primary 'dead' generation resulting from the standing position (Fig. 9.12c). In case of broken statues, the older generation of runnels continues over multiple fragments (Figs. 9.14a–c and 9.15a, b) which is evidence corroborating the original upright position. However, in some cases, the younger generation of runnels continues over the break scars created by fragmentation. This observation has some archaeological consequences. The fragmentation of a lot of *moai* of Easter Island is commonly considered as a result of violence. During tribal wars, islanders would have toppled images and destroyed several *ahu*. However, a large part of the fragments of the statues is still found adjacent. Some years ago, we proposed an explanation of this strange situation: perhaps the segmentation occurred sometime after the statues were laid down, but not during the laying down process itself (Cauwe 2011; Fig. 9.14). In this case, the *moai* was surely intact after it was put in a horizontal position, and the breakage occurring later, by stresses created from the overhang or bending. This hypothesis is demonstrated by the continuity on some isolated images of the secondary runnel network covering the fragmented surfaces; impossible circumstances if the *moai* were broken at the moment of their fall.

Other *moai* have the top of their head intact, without major alteration by rainfall-generated erosion. This phenomenon is only possible if the head had a protective cover, such as a *pukao* for example. This case was observed at Ahu Matá Ketu, where a *moai* is laying on the ceremonial terrace of an *ahu*. At the back of the monument, lays an isolated *pukao* which is most possibly the headdress of the *moai* and the top of head is not affected by weathering (Fig. 9.16a, b). This demonstrates that a careful and detailed geomorphological analysis of the *moai* may add considerable evidence to unveil their story.

Fig. 9.16 Ahu Matá Ketu (inland platform). A *moai* is now laying in front of a monument (**a**). Back from the *ahu* lays an isolated *pukao* (**b**). Maybe the *moai* and *pukao* were once together as the head of the statue has no damage due to weathering

5 Some Strange *Ahu* near the Antique Roads

We have seen that there are two different classes of *moai*, one characterised by bevelled eyes and the other by sockets for coral or obsidian inlay. Furthermore, the head for the majority of the statues scattered along the ancient roads (with bevels), as well as the complete ones left in and around Rano Raraku, are a third of the total body height when compared to *moai* on the *ahu* where the head represents only a quarter of the body height. Finally, the width of the bodies of the *moai* from the *ahu* is symmetrical while the road-*moai* often have a large base that stabilises the statue in an upright position without the support of any additional architecture, except small platforms (Heyerdahl et al. 1989), or stone plinths (slabs) (Hamilton 2013).

But there are some exceptions to be found on four *ahu* platforms where the *moai* of road, or Rano Raraku type, with big heads, bevelled eyes, and a large base have been installed. The most impressive site is inland, not too far from La Pérouse Bay [without a number on Englert's map (Englert 1974); probably number 59 in Martinsson's inventory (Martinsson-Wallin 1994)]. The second one is also located inland, not too far from Hanga Poukura (Ahu Matá Ketu; number 230 on Englert's map; number 140 in the Martinsson's inventory). A third one is at Ahu Oroi, closed to the south coast (number 199 of Englert's map; number 116 in the Martinsson's inventory). Finally, a *moai* without eye sockets is associated with Ahu Hanua Nua Mea (centre of the island, at Ava Ranga Uka A Toroke Hau). Confronted with these situations, the first hypothesis is that some *ahu* received statues of the road type that are similar to the last period of manufacture of Rano Raraku statues. In this sense, these four inland platforms would be the most recent statues carved from the quarries although the architecture of these monuments is also out of the ordinary.

Ahu Matá Ketu does not appear to be an actual platform. We can only observe the back wall of a hypothetical platform since there are no traces of a front wall, wings or ramp. Moreover, the current positioning of the boulders in the back wall are precariously balanced on the foundations and a quick observation allows us to see that these blocks could never offer much support (Fig. 9.17). It is beyond doubt that such a fragile and elementary construction would not have supported a large statue of several tonnes. It could be argued that the platform was destroyed and that the statue is now laying in front of these ruins.

Another aspect, we cannot explain about Ahu Matá Ketu is the complete disappearance of the front wall. If it was present near the base of the toppled *moai* it would have protected part of the structure and prevented stone scavenging. Moreover, it is impossible to imagine the destruction of all of the front wall before the toppling of the *moai*, as it would collapse during that effort. An incomplete *ahu* and an abnormal type of statue suggest that maybe Ahu Matá Ketu is an incomplete structure or even something like a sham! Furthermore, the prone *moai* covers a grave. This is not an exceptional occurrence as elsewhere around the island, there are tombs below some prone *moai* at several *ahu*. For example, there are present at

Fig. 9.17 The back wall of Ahu Matá Ketu

Ahu te Niu (Cauwe 2011: 71–72), Ahu Tahira (Vinapu; Mulloy 1961: 95–115), Ahu Hanga Poukura and Ahu te Peu (Smith 1961: 189–194).

A similar situation occurred with the *ahu* in the vicinity of La Pérouse Bay. On the basalt block cairn which covers the ramp of the monument, the islanders had excavated two burial pits covered by a pair of *moai* of the road type. Once again, the two statues seem too big for the platform, and there are no traces of pedestals for them. Moreover, their position is abnormal. They are located on the top of the cairn, and not within or beneath it (Fig. 9.18). If these images came from the *ahu*, the Rapanui moved them away from the ahu platform, then built the cairn, and finally, they moved the *moai* and placed them above the cairn. This hypothesis proposes a very complicated series of events. A simpler one (Ockham's razor!) is to accept the proposition that the Rapanui scavenged two *moai* from along an ancient road (the monument is near the 'Northern Image Road' of Routledge, the 'Road A' of Hunt & Lipo) and used them as a roof for two burial vaults dug through the ramp of the old platform.

Ahu Oroi is along the 'Southern image Road' of Routledge ('Road E' of Hunt & Lipo). In fact, this monument is a natural outcrop of basalt with some partial walls constructed on top of it. It is an opportunistic monument with a platform for large erected images. Once more, the *moai* has bevelled eyes and covers several burial vaults.

Finally, the complete *moai* lying face down on the ground on the ramp of Ahu Hanua Nua Mea is only damaged by the environmental elements of wind, sun, rain, marine spray, and lichen growth. Because of its location on the *ahu* ramp, it appears to be in process of installation and part of this process would have been the carving of the eye sockets. The traditional explanation for the absence of eye sockets would

Fig. 9.18 An inland *ahu* near La Pérouse Bay. Two large *moai* are laying on the top of the closing cairn and covering two graves. Despite the big size of the statues no traces of a pedestal were found on these monuments. Actually, the association between the platform and the images is maybe recent, with the placement intended to close the two tombs dug through the ramp of the *ahu*

be that the process of installation was suddenly interrupted, and the context of the statue provides some support for this interpretation.

Nevertheless, there is an argument that can be made against the idea of carving of the sockets after the moving of the statues were completed. The evidence is the elongation and narrowness of the head of most of *moai* without eyes, and the greater width of the head of most statues on *ahu* [see the categories established by Van Tilburg (1994: 22–23)]. It seems that the operation is also sculpturally unrealistic since the head of many *moai* without eye sockets is too narrow to be transformed into a wider one. But the discussion is of secondary importance for our case of study. Indeed, it has been established that the *moai* of Ahu Hanua Nua Mea was upright before it was deposited face down on the ground; a circumstance that does not work with the hypothesis of an unfinished statue that was never used. If we summarise the facts, the image of Ahu Hanua Nua Mea was upright before its horizontal deposit; it is today laid down on top of the stone covering the level of the *ahu* (Fig. 9.19). For this last reason, we can propose the provisional conclusion that the statue found today lying down at Ahu Hanua Nua Mea was never erected on the altar. It was first standing elsewhere, and moved later to its current horizontal position after the use of Ahu Hanua Nua Mea had ended. This explains its position above the sealing layer of basalt stones placed over the monument.

Fig. 9.19 The *moai* of Ahu Hanua Nua Mea is lying down on top of the sealing level of the *ahu* and is not partially buried as is usual

6 Discussion

The new geoarchaeological approach to understanding the use-history of the *moai* scattered along the roads asks that several observations must be considered before an interpretation.

1. It seems evident that all these statues were upright for a long time (several decades minimum). This fact is evidenced by the formation of a first network of runnels produced by rainwater runoff.
2. The absence of damage to most *moai* indicates they never fell from a vertical position by accident during their transportation.
3. The analysis of the base of these *moai* indicates they were carved for emplacement in an upright position. A majority of the statues have a large base, sufficient to keep them in a vertical position on the ground without the help of any supportive architecture such as pedestals. On the other statues with a smaller base, the runnels stop systematically a few centimetres above the base, indicating these *moai* were slightly buried below the surface and were supported by a platform or plinth.
4. At some point in time, the *moai* were laid down into a prone position on the ground with care. Indeed, 93% of them are intact and the broken ones do not exhibit a scattering of their fragments. From this moment onward, a secondary network of runnels, reflecting the new horizontal position, started to form and is still active today.
5. The laying down of the statues was premeditated since 62% of them are augmented with chocking stones or positioned on pavements or on older structures.

There is some information that give clues about the chronology of these events. The *moai* along the roads belong are of the same form as the ones erected around, or inside, Rano Raraku. Therefore, there is a high probability that the statues set up on the slopes of Rano Raraku are late in time. One of them (Statue 263) has on his stomach an engraving of a ship from the eighteenth century. The engraving could be more recent than the *moai* itself, but when the petroglyph was discovered by the Norwegian expedition in 1955, it was on a fresh statue, without significant alteration by weathering. Henceforth, statue and drawing likely belong to the same period.

In addition, at the end of the eighteenth century, William Wale speaks about one erected *moai* in the south-eastern sector of the island, but at the middle of the next century, no statues were still upright on the island except those on the slopes of Rano Raraku. As well, *moai* were erected vertically along the roads before the end of the use of the quarries (middle of the seventeenth century?). Some decades later, before the end of the eighteenth century and after the visit of Wale, the islanders completed the lowering process. The operation was finished no later than the middle of the nineteenth century.

Taking all these facts and their chronological framework into account, it is difficult to accept a simple story of *moai* abandonment along the ancient roads during statue transport. We argue that abandonment is not an appropriate inference because the form of these *moai*, their context, and natural alteration support their upright positioning. Accidental breakage or violence and defacement must also be rejected because of the good conservation state of a majority of statue and by the premeditated lowering of the *moai*.

The shape of the *moai* base also brings into question other reconstructions of statue transport and modification. Lipo et al. (2012) recently proposed that a larger base would facilitate the moving of the *moai* since a large base would be adapted for ‘walking statues’. When the images reached their destination and were in place in front of an *ahu*, islanders re-carved the base region and sculpted the eye sockets (Lipo et al. 2012). This hypothesis neglects two facts. First, the size of the *moai* found on the road is different from those positioned on the platforms, not only with regard to the type of base but also because the proportions of the head and the height are different. If the statues along the roads were destined to *ahu*, then it was necessary not only to re-carve the base and the eyes as proposed by these scholars, but also the whole body. Why would the islanders move a lot of large statues that only approximated the finished product desired for *ahu* platforms? If the hypothesis of Lipo, Hunt and Rapu is correct, it would mean that late in the period of *moai* carving the Rapanui people changed their conception of an ideal type of *moai*.

7 Conclusion

Setting aside the hypothesis of *moai* abandoned during their transportation and looking at the evidence with care allows for a more meaningful interpretation. It appears that the Rapanui built procession roads (see Routledge 1919: 196–197), which were lined with tall *moai* and which led to Rano Raraku at a time when the quarries were a source of sacred images. Perhaps, the islanders considered Rano Raraku itself as a sacred site, and the tuff as sacred material too. This is not without parallel in Polynesia as the sacred character of nephrite (*pounamu*) documented in New Zealand (Brailsford 1996; Chambonnière and Maine 2017; Robley 1840), and processional roads have been reported from the Hakaui valley on Nuku Hiva in the Marquesas (Radiguet 1929). During the eighteenth century, the Rapanui started to lay down the statues, exactly at the same time and in the same way as the was done to the images on the ceremonial platforms (Cauwe 2011; see also Chap. 15 in this volume)—in both cases with due caution.

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Chapter 10
Platforms in Motion: A Genealogical Architecture

Nicolas Cauwe

1 Introduction

The first European travellers to Easter Island were fascinated by the presence of large images erected on stone altars or platforms. Both Jacob Roggeveen (1838: 112) and those who followed him gave unequivocal descriptions that some *ahu-moai* were still in use during the eighteenth century, even if some testimonies, like that of George Forster in 1774, mention monuments appearing abandoned, with their statues lying prone in front of some monuments (Thomas and Berghof 2000: 316–317). However, in 1838, Abel Aubert Du Petit-Thouars gave the last description of upright statues (Du Petit-Thouars 1840–1841, vol. 2: 225–226). The testimony of the French admiral is somewhat ambiguous, his observations having be made only from his ship, without disembarking on the island. The next visitors never had the opportunity to observe any *moai* still upright on a platform.

It remains to understand the seemingly disarticulated appearance of Rapa Nui *ahu*. Were they result of negligence, non-maintenance, and therefore inevitable ruin? Could it be the result of voluntary acts, eventually iconoclastic and/or violent, of the Rapanui people putting an end to a secular tradition? An idea, presented by William Thomson (1891: 499) and updated more recently by Edwards and Marchetti (1996), is that of natural disasters, such as tidal waves or earthquakes (Fig. 10.1). This thesis is quite possible for some monuments, but it is difficult to imagine the repetition of such natural phenomena for more than a century, until all the stone giants of the

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_10

Fig. 10.1 Ahu Tongariki. In 1960, an earthquake off the coast of Chile caused a tidal wave which destroyed the *ahu*. This exceptional disaster cannot explain the toppling of all statues on Easter Island. The photos of the same monument, taken in 1934 by the French-Belgian expedition, or by Heyerdahl 20 years later show the statues of Ahu Tongariki, face to the ground, neatly arranged in front of the platform. This configuration is incompatible with a natural catastrophe

island had collapsed. Nature is not really accustomed to such a perfectly exhaustive work. On the other hand, a lot of statues, or images, are neatly arranged in front of the platforms, a positioning incompatible with catastrophic natural events.

The current and most popular hypothesis is that which invokes war and violence, that lead to a destruction of the cultural heritage (Bahn 2015; Bahn and Flenley 1992, 2011; Flenley and Bahn 2002; Diamond 2005). The main argument is the concomitance of a radical environmental change and the destruction of the *ahu* images. Moreover, the oral tradition, recorded at the end of the nineteenth century and at the beginning of the next one, relates episodes of war. Nevertheless, very few testimonies have been recorded about the collapse of the *moai*. Katherine Routledge noted in 1914–1915 in a statement more about legend than fact:

> No one now living remembers a statue standing on an ahu; and legend, though not of a very impressive characters, has already arisen to account for the fall of some of them. An old man arrived, it is said, in the neighbourhood of Tongariki, and as he was unable to speak, he made known by means of signs that he wished for chicken-heads to eat; these were not forthcoming. He slept, however, in one of the houses there, and during the night his hosts were aroused by a great noise, which he gave it to understood was made by his feet tapping against the stone foundations of the house. In the morning it was found that the statues on the great ahu had all fallen: it was the revenge of the old man. Such lore is, however, mixed up with more tangible statements to the effect that the figures were overthrow in tribal warfare by means of a rope, or by taking away the small stones from underneath the bed-plates, and thus causing them to fall forward. That the latter method had been used had concluded independently by studying the remains themselves (Routledge 1919: 173).

Fig. 10.2 Ahu Hanga Tee. The organized aspect of ruins. Here, the statues are intact and perpendicular to the platform, an order not characteristic of destruction by violence

Therefore, there could have been wars, and it is easy to imagine the destruction of the island heritage during these conflicts. There are many other Rapa Nui legends where wars, crimes, revenges, or killings abound. Tahiti, Marquesas Island, or New Zealand have also given abundant accounts of similar brutalities; the traditional Polynesian world was anything but tender (Henry 1928; Laval 1938; Radiguet 1882).

However, we can oppose this thesis of a prolonged crisis which would have lasted at least a century if we refer to the material evidence of the eighteenth and nineteenth centuries. This includes the ‘organized’ aspect of some ruins where statues are lying down parallel to each other in front of the platforms (Fig. 10.2), the island-wide occurrence of the statue toppling (it is rare that conflicts destroy everything without exception), and finally, the absence of European testimony of war during the eighteenth century makes the hypothesis of a systematic destruction by violence more difficult to accept, but the possibility of sporadic deliberate damage is certainly admissible.

The excavations organized between 2001 and 2008 around serval *ahu-moai* reopen the debate. The data collected at Ahu o Rongo in Hanga Roa (Huyge and Cauwe 2002), Ahu Motu Toremo Hiva near Poike (Cauwe et al. 2006, 2010), and Ahu te Niu north of Te Peu Sector (Cauwe 2011) forces us to rethink the story of the *ahu* platforms, including their early development, even before the collapse of the images. A complex story has now emerged, and the motivations for it are undoubtedly multiple and complex.

2 Sequences of *ahu*

At Ahu o Rongo (Fig. 10.3), close to the *caleta* of Hanga Roa (27.145168° West/109.429899° South), a sequence of two *ahu* platforms was found. The oldest platform (Ahu I) is the one that had supported the statue made of grey basalt shipped to Belgium in 1935. The two or three images from the last construction (Ahu II) were partly destroyed by the French expedition of *La Flore* in 1872. We have obtained multiple ^{14}C dates for Ahu I. According to the results, which are remarkably similar for the three samples, this old monument was in use during the latter part of the thirteenth century and/or during the fourteenth century AD (Table 10.1). The transition period, between Ahu I and Ahu II, was dated by obsidian hydration to the middle of the fifteenth century (Table 10.1). Therefore, Ahu II was built after the middle of the fifteenth century (Huyge and Cauwe 2002).

A similar situation was found at Ahu Kiri Reva (previously named Motu Toremo Hiva) on Poike peninsula (27.094620° West/109.249802° South) (Fig. 10.4), where a sequence of three platforms was encountered (Cauwe et al. 2006, 2010). There, the chronological framework is less well defined (Table 10.1), but the construction events took place between the end of the thirteenth century and the eighteenth century at the latest. The first monument (Ahu I) and the second one (Ahu II) were built during the fourteenth century. These two platforms are not superimposed. The second *ahu* is located at the East of Ahu I. But stratigraphic evidence shows the posteriority of Ahu II. Finally, a third *ahu* (III) was on top of the two previous ones after the fifteenth century.

Fig. 10.3 Ahu o Rongo. This double *ahu* was preceded by a first monument that supported a statue later shipped to Belgium in 1935 (excavations of the Royal Museums of Art and History of Brussels)

Table 10.1 Dates of Ahu o Rongo (Hanga Roa), Ahu Motu Toremo Hiva (Poike Peninsula), and Ahu te Niu (Western coast, at the north of the Te Peu Sector)

Samples	Lab no.	BP	Cal AD (2 σ)
Ahu o Rongo			
Charcoal 'cremation' area against Ahu I	GrN-26,318	715 ± 35	1270–1400
Charcoal between Ahu I & II	GrA-18,378	655 ± 30	1290–1410
Charcoal below South wall Ahi I	GrA-18,380	655 ± 35	1290–1410
Obsidian flake between Ahu I & II (Obsidian hydration date)	DL-2001-88	525 ± 67	1425
Ahu Motu Toremo Hiva			
Agricultural activities between the use of Ahu II & III	KIA-26487	240 ± 20	1640–1800
Foundations of Ahu I	KIA-26452	675 ± 20	1295–1395
Foundations of Ahu I	KIA-26461	630 ± 25	1310–1420
Foundations of Ahu II	KIA-26453	675 ± 25	1295–13,995
Foundations of Ahu II	KIA-26464	700 ± 25	1280–1400
Ahu te Niu			
Grave dug through the sealing level of Ahu II South	KIA-45378	445 ± 25	1415–1475
Human bone inside the sealing level of Ahu II North	KIA-45379	220 ± 25	1640–1960
Human bone inside the sealing level of Ahu II North	KIA-45381	230 ± 25	1640–1960
Human bone inside the sealing level of Ahu II North	KIA-45382	220 ± 25	1640–1960
Charcoal between Ahu I South and Ahu II South	KIA-45383	360 ± 30	1450–1640
Nutshell, garden (*manavai*) between Ahu I South and Ahu II South	KIA-45386	560 ± 25	1310–1430
Charcoal, foundation of Ahu I South	KIA-45387	390 ± 25	1440–1620
Nutshell, foundation of Ahu I North	KIA-45388	520 ± 25	1320–1450
Charcoal, foundation of Ahu I North	KIA-45389	460 ± 25	1410–1460
Charcoal, garden (*manavai*) between Ahu I South and Ahu II South	KIA-45390	450 ± 35	1400–1610

GrN: Groeningen laboratory; KIA: Royal Belgian Institute for Cultural Heritage laboratory; calibration using OxCal v3.10 (Bronk Ramsey 2005) and Southern Hemisphere atmospheric data (McCormac et al. 2004)

At Ahu te Niu (27.088721° West/109.407528° South) (Fig. 10.5), we can observe a sequence of two twin *ahu* where two monuments are superimposed at the South of the site, and two others at the North (Cauwe 2011). Here too, the stratigraphic evidence indicates that the oldest monuments (Ahu I South and Ahu I North) were not built at the same time. It seems that Ahu I North was constructed between the second part of the fourteenth century and the first half of the next one. Ahu I South is slightly more recent (second half of the fifteenth century or the beginning of the sixteenth century). The twin recent *ahu* (Ahu II North and Ahu II South) were also created at different moments based upon our stratigraphic data, but were partially

Fig. 10.4 Ahu Motu Tomero Hiva. On top of the northern cliff of Poike, this site shows a sequence of three monuments (excavations of the Royal Museums of Art and History of Brussels)

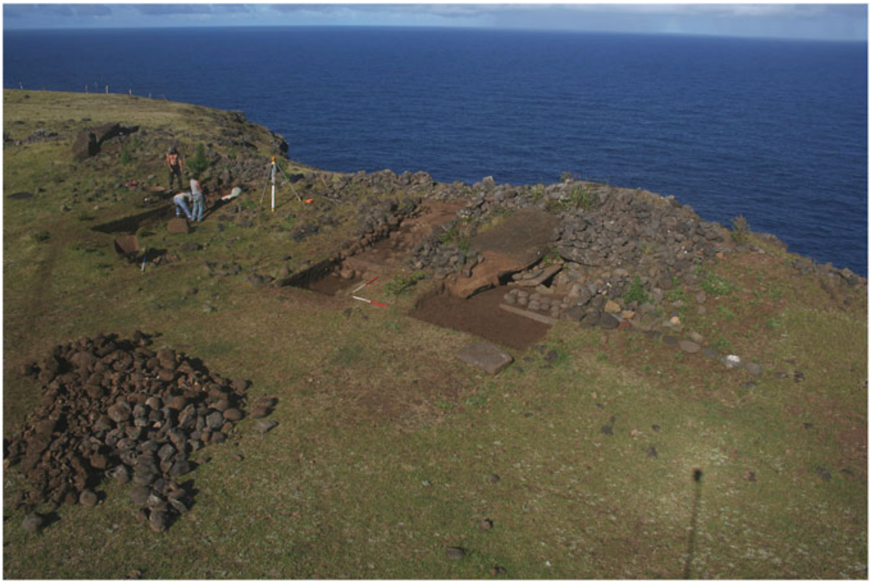

Fig. 10.5 Ahu te Niu. During the excavation, we have found four successive platforms (excavations of the Royal Museums of Art and History of Brussels)

contemporaneous, probably during the second part of the seventeenth century or during the eighteenth century (Table 10.1).

The accumulation of monuments at one location is definitively not a novelty for Rapa Nui. It was determined first by Carlyle Smith and William Mulloy during the Norwegian expedition of 1955 (Smith 1961; Mulloy 1961) and confirmed some years later by William Mulloy (Mulloy 1966, 1968, 1970, 1973). The first conclusion was that the *ahu* sequences offered evidence for a story of the island organized in three periods: Early (then estimated between AD 400 and AD 1100), Middle (AD 1100–1680), and Late (after AD 1680). As usual, the Early period was considered as the ‘archaic’, with simple *ahu* without images; the Middle Period was the ‘classic’ one, with the most statuary, and finally, the Late period is the time of decadence, with the toppling of the *moai* (Smith 1961: 218–219).

It appears today that this schematic structure is erroneous. The recent excavations show that each site has had its own story, with two or three stages, or sometimes four periods of construction. The development of the monumental architecture of Easter Island cannot be divided into periods but it was characterized by cycles of *ahu* abandonment and their regular reconstruction, each site having its specific rhythm. We can just recognize two general periods: the first one with the cycles of deconstruction and rebuilding of the *ahu* images occurring from the beginning of island settlement to the middle of the seventeenth century), and the second one lasting until the first contacts with Europeans, which is characterized by the definitive abandonment of the *ahu*, the toppling of the statues, and the covering of the monuments by piles of stones.

Elsewhere in Eastern Polynesia, we can observe the same phenomenon; that of the ephemeral character of monuments and their regular reconstruction (Cauwe 2022). The question is therefore no longer to recognize periods, but to understand the reasons for the cycles of regular reconstruction of monuments. We know, however, that in Polynesia the aristocracy had to show its capacities, as birth alone was not enough to ensure rank and leadership. Did the regular reconstruction of religious platforms participate in this requirement, by enabling chiefs to assert their abilities and power? But there is more. Testimonies collected some decades ago indicate that Polynesians had a genealogical conception of all aspects of the world, including monuments (Métraux 1940: 107). Could closures and reconstructions of *ahu-moai* represent the genealogy of the monuments? The recovery of fragments of old statues to integrate them into the masonry of new altars seems to be part of the same principle.

For the Society and Tuamotu archipelagos, Teuira Henry mentions lineage needs to justify the regular reconstruction of new monuments. The demographic evolution of the clans sometimes required the expansion of the territories, and the *marae* also served to guarantee the land possessions of each clan, thanks to the genealogy they symbolically contained. At the end of the nineteenth century, Tahitians were still able to describe all the filiations concerned by a particular monument, almost every stone representing a member of a lineage (Henry 1928: 141–144).

But the regular reconstructions could also be a response to economic and religious necessities. It is obvious that the construction of an *ahu-moai* required the mobilization of a workforce, its remuneration and the organization of its subsistence needs. A whole economic machine was thus set in motion: food production, extraction and transport of raw materials, shaping the slabs for the platforms, and the sculpture of statues. In addition, whole sections of the politico-religious structure were also activated. Taboos were lifted to acquire resources and ceremonies were necessary for closing an *ahu*, and then for the opening of the following ones where 'ancestralization' of deceased chiefs occurred.

The question of the motivation for the regular reconstruction of the *ahu* remains open. But it is evident that the phenomenon affects a large part of Eastern Polynesia and not only Easter Island. The answers are to be found in contingencies that escape practical or material issues. Obviously, the cycles of rebuilding of the *ahu-moai* belong to cultural needs, and they are not the result of technical reasons or of the phasing of the history by the Islanders.

The discovery in recent excavations of remains of ceremonies to organize the closing of monuments before their reconstruction supports the hypothesis of cultural necessities. Thus, some statues were removed and reused, complete or fragmentary, for new constructions. This fact is well illustrated at Ahu Maitaki te Moa where a complete *moai* was built into the back wall of the last platform (Fig. 10.6), or at Ahu Nau Nau, where a head was incorporated into the masonry of the seaward wall (Fig. 10.7). But many other monuments show the reuse of fragments of bodies, eventually recarved (Fig. 10.8).

At Ahu Motu Toremo Hiva and Ahu te Niu, we have found also traces indicative of the removal of some cobbles (*poro* and small rounded sea stones) that covered the ramps in front of the platforms (Fig. 10.9). We cannot prove that the cobbles taken away were reused for new constructions. Nevertheless, there is an interesting testimony from Tahiti, recorded by John Orsmond during the nineteenth century, and published by his granddaughter, Teuhira Henry:

Fig. 10.6 Ahu Maitaki te Moa. A completed statue is incorporated into the back wall of the *ahu*

Fig. 10.7 Ahu Nau Nau. The head of a *moai* inside the masonry of the seaward wall of the platform

Fig. 10.8 Ahu Te Pito Kura (detail of the seaward wall). In a lot of *ahu*, we can see reuse of *moai fragments* eventually recarved, as this slab of Rano Raraku tuff at the west corner of the back wall

> When all the stones were collected, the ground for the marae was cleared and then sprinkled well by the priests with sea water to make it holy. A long stone was taken from some other grand marae, as the ‘ofa’i-faoa (chief-corner-stone), a man was slain and placed in the hole dug to receive the stone -his spirit supposedly remaining to guard the marae- and the erect stone was planted firmly upon the corpse, while the priest prayed to the tutelar god [. . .] (Henry 1928: 132).

Fig. 10.9 Ahu te Niu. Some pebbles of the ramp of Ahu North II were taken away. The same phenomenon was noted at Ahu Motu Toremo Hiva

Fig. 10.10 Ahu Motu Toremo Hiva. Deposit of a layer of red scoria (*hanihani*) in front of the *ahu*. This process was found above all the terraces of the *ahu* recently excavated

Finally, we have observed on different sites the deposition of a layer of red scoria (*hanihani*) in front of the *ahu* (Cauwe 2011) (Fig. 10.10). There is no doubt about the voluntary and organized nature of these layers. In addition, the stratigraphic data reveal that the *hanihani* was systematically deposited after the

Fig. 10.11 Ahu te Niu. Planting of a palm tree, between two construction phases of the monument, in the centre of a circular *manavai* (stone surface)

end of the use of a monument and before its reconstruction. We infer that the platforms were abandoned, or at least no longer maintained, as seen from amount of natural sediment on their ramps, which must have accumulated over years, rather than weeks or days. Then, the Rapanui returned to these sites and laid a layer of red scoria on them. This was followed by another period during which the ramps were again covered by natural sediment. It was only after these stages that a new altar was built. The significance of the red dust escapes us, but the stratigraphic sequences, in which the layers of red scoria appear, make it likely that the closing of an *ahu-moai* was an operation which could require several years.

This long-term process is also illustrated at Ahu te Niu by the planting of a palm tree, between two construction phases (Fig. 10.11). This presence of a tree is not accidental. The traces of the roots were observed in the centre of a *manavai* (stone enclosure). The growth time of such a tree required to develop a noticeable root system indicates the extended duration of the closing process of an *ahu*.

3 The Dismantling of the Last Plaforms

The last generation of monuments, those still visible on the surface and probably in use during the seventeenth and the eighteenth centuries, suffered a more complex story than the previous ones. They have also show evidence for the removal of pebbles and the deposit of red dust. But the images were toppled around the platforms and never reused. In addition, platforms and statues were covered with

Fig. 10.12 Ahu Vinapu. During his excavations in 1955, William Mulloy has only cleaned the northern half of the monument, and beneath the large layer of stones (with cobbles and coral), he found not only the intact altar, but also the ramp without any damage

basalt stones, giving them the appearance of ruins. In reality, these stones were used to seal the sites, without destruction of them, except the toppling of the *moai*.

The well-preserved condition of the platforms beneath the accumulation of stones was demonstrated by William Mulloy in 1955, with his excavations of Ahu Vinapu (Mulloy 1961) (Fig. 10.12). Only the northern part of the monument was cleaned by him, and beneath a large layer of stones (with pebbles and coral), he found not only the intact platform, but also the ramp without any damage. However, Mulloy concluded that the last use of the site was the result of *internal warfare and abandonment of the pratice of working large stone* (Mulloy 1961: 160). He gave no explanation about the covering of the monument by thousands and thousands of stones. The good conservation of the latest *ahu*, despite their covering by piles of stone, is now definitively validated by recent excavations (Figs. 10.13, 10.14, and 10.15).

Two conclusions are called for based upon the above discussion. First, except the overthrowing of the images, the platforms were never destroyed. Second, the *ahu-moai* were deliberately covered by stones to close their traditional use (Cauwe 2011). We must discuss the overthrow of the *moai*, but for the remaining structural features there are no traces of destruction, only the burial of monuments under thousands of stones that had to be collected, moved, and piled up. Some will see this arrangement as the work of enemies wanting to destroy the symbolic power of their opponents. But this is not the only solution, since recent excavations have shown that there was a time period of a few years between the falling of the statues

Fig. 10.13 Ahu o Rongo. This monument (Ahu II) shows one of the most beautiful sealing levels, built with large cobbles particularly well positioned. Definitively, the accumulations of stones above monument are not the result of ruin or destruction

and the sealing of the *ahu-moai*. Therefore, the two events are not connected. Even if the collapse of the images was perhaps the result of conflict, the sealing of the monument addresses other concerns which may include symbolic burial, protection of collapsed statues, distrust of *moai* who failed to prevent their own overthrow. The are many potential explanations, but without direct testimonies or archaeological facts it is difficult to choose which are the most believable.

There are two additional considerations. First, all the stone covered monuments have been reused as a necropolis for numerous burials. The most demonstrative case is that of Ahu Kihi Kihi Rau Mea (western coast). There, no less than 17 graves were found, dug through the stone layer built on top of the former platform (Seelenfreund 2000). At Ahu te Niu, we have discovered five tombs, but the monument was not completely excavated (Cauwe 2011). Again, survey indicates that the phenomenon

Fig. 10.14 Ahu te Niu. Beneath the surface layer of stones, we can see the intact ramp, except for a pit dug to bury a statue overthrown with care (without any damage)

Fig. 10.15 Unmamed *ahu* of the south coast. This monument seems to be in ruins, but on both extremities of the pile of stones we can see the undamaged corners of the platform

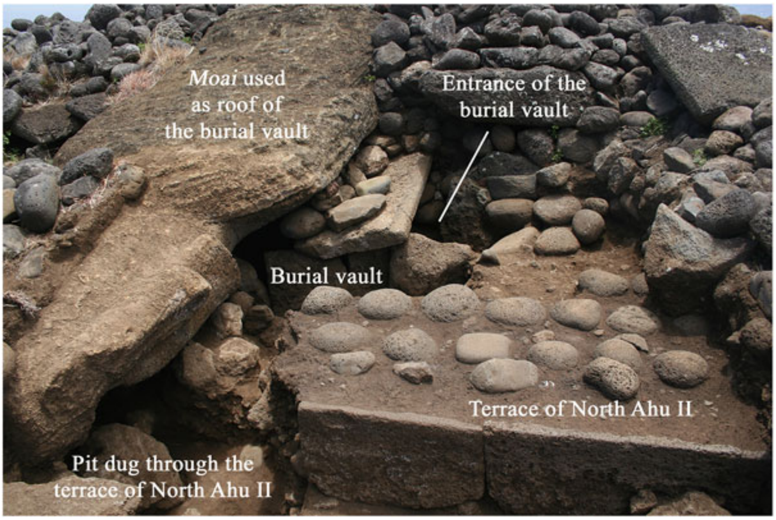

Fig. 10.16 Ahu te Niu. The statue buried on the ramp of the monument was used to cover a burial vault

affects all the *ahu-moai*. Whatever the reasons for the sealing by stones, religious sites have continued to exist, but for new needs.

The second consideration are the circumstances surrounding the overthrow of the images. It is interesting to note that the majority of the *moai* are intact, despite their fall from the platform; a situation impossible to explain if the fall was made with a violent intent and without any respect. There are some cases for damage to *moai* which brutality or accident are the best explanations, but they are not applicable to all situations. Along the southern coast, we can see in front of the large *ahu* intact images neatly arranged face to the ground (Fig. 10.2). Is it the result of warfare and destruction? At Ahu te Niu, in front of Ahu II North, a *moai* is even used to cover a burial vault, which is perfectly built with carved slabs (*paenga*) (Cauwe 2011) (Fig. 10.16). The same situation can to be observed at Ahu Poukura (south coast) (Fig. 10.17), Ahu Tepeu (Smith 1961), or Ahu Tahira (Vinapu) (Mulloy 1961) (Fig. 10.18). Definitively, the overthrow of a majority of images is not the consequence of intentional destruction. The operation was conducted with care, sometimes to cover graves and frequently without causing damage.

Fig. 10.17 Ahu Hanga Poukura. A statue partially buried in front of the monument (**a**). In fact, this *moai* covers a burial vault, its forehead incorporated into the masonry of the burial (**b**)

Fig. 10.18 Ahu Tahira. This site was excavated in 1955 by William Mulloy. The three *moai*, serve as the support for the roof of a large burial vault

4 Conclusion

At all times, the platforms for ancestor worship have evidenced closures by organized principles of taking away of the statues, rounded stones, and pebbles (*poro*) of the ramp, depositing the dust of red scoria and sometimes planting trees in front of the platform. The last generation of monuments have shown the same story, and there is no reason to believe that the motivations were different from those of previous centuries.

The only differences between the earlier and later periods were the overthrow of the statues and leaving them close to their former platform. This last fact, frequently interpreted as the result of violence is simply an assumption.. There is no longer any doubt our alternate interpretation, if we consider the good state of preservation of the *moai*, their arrangement in front of the platform, and their occasional use to cover graves. Thus, there are very few material indicators of violence that would justify the closing of the last platforms for reasons of conflict. Such tragedies of violence may have exited sporadically during prehistory, but all of the testimonies from the eighteenth century, and the results of recent excavations show monuments becoming necropolises for burials.

There is currently insufficient data to explain these changes which were not sudden but taking place over at a century or more. Are they adaptation to environmental changes? It is possible, but there are other potential explanations. At approximately the same time when the Rapanui closed *ahu*, they turned the western rim of the Rano Raraku volcano into a sacred place and developed at Orongo a cult dedicated to the god *Makemake*. Are we seeing a transition from ancestors to divinities? The Polynesians have vast pantheons, expressed in many mythologies. In short, rather than a change of religion, it is possibly a change in the balance of power between gods and ancestors.

The phenomenon is not specific to Rapa Nui as several Polynesian islands also put elevated divinities, such as ‘Oro in Tahiti or Hikuleo in Tonga. This convergence of comparable facts in different places prompts us to look for the causes beyond local anecdotes. However, ancestors only interfere with their descendants, while the gods impose their law on everyone. Substituting the gods for the ancestors is to move from a fragmentary society to one of more global management... perhaps to meet new challenges. What were these challenges? An acceleration of demographic growth seems possible. Such a situation needs economical and social answers, sometimes result of period of violence. The history of the *ahu-moai* shows that it was more likely a more peaceful process that was at work in Rapa Nui.

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Part III
Climatic and Environmental Change

Chapter 11
Climatology of Rapa Nui (Isla de Pascua, Easter Island)

Raymond S. Bradley, William J. D'Andrea, Henry F. Diaz, and Liang Ning

1 Introduction

Rapa Nui (Isla de Pascua, Easter Island) is one of the most remote of the Polynesian islands, lying ~3700 km west northwest of Santiago, Chile, and 2000 km from the nearest inhabited island (Pitcairn) to the west. It is most famous for its iconic statues (moai) that were carved from local volcanic rock by the first settlers on the island who arrived in the twelfth century AD (radiocarbon dating of the initial colonization of Rapa Nui is in the range 1150–1290 cal. AD; Di Napoli et al. 2020). Much has been written about the cultural history of the island, and of the ecological changes that occurred over the following centuries, and these accounts offer widely different interpretations (e.g. Flenley and Bahn 2003; Diamond 2005; Hunt 2007; Rull et

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_11

al. 2018; Rull 2020). Some argue that climate change was an important factor in causing the ecological (and subsequent societal) changes, while others point to the paramount importance of cultural and socio-economic factors. However, current evidence indicates that despite major changes in natural vegetation that followed the arrival of people, the population managed to maintain sufficient agricultural production for their needs. A shift toward drier conditions may have played a role in the cultural upheaval that occurred in the sixteenth to seventeenth centuries (Mann et al. 2008; Rull 2020), but it was the arrival of Europeans in the eighteenth century that brought really catastrophic changes to the island, through the introduction of infectious diseases and the transfer of many indigenous people to South America as slaves.

Despite considerable interest in the past climate of Rapa Nui (Rull 2021), very little attention has been paid to the modern climate of the island. Climate variability is of particular importance to Rapa Nui today, because of the tremendous increase in pressure from tourism. The island is only ~164 km^2 in area (about three times the size of Manhattan, New York); the resident population is ~7750 (in 2017) but more than 100,000 tourists visit the island annually, greatly increasing the demand for water, power and local agricultural products. Here, we review the climatology of Rapa Nui, with a particular focus on interannual variability and recent changes in rainfall that have had dramatic effects on the hydrology of the island.

2 Large-Scale Circulation

Rapa Nui is situated on the western flank of the Southeastern Pacific sub-tropical high-pressure system (STHP), which defines the descending limb of the southern hemisphere Hadley cell (Chen et al. 2014) (Fig. 11.1). However, the South Pacific Convergence Zone (SPCZ) to the west of Rapa Nui controls moisture flux to the island, as seen in total column precipitable water vapor (Fig. 11.2).

Seasonal variations in the strength and position of the STHP and SPCZ greatly affect rainfall totals in Rapa Nui (Steiger et al. 2022). The island is situated close to the boundary, at which annual evaporation exceeds precipitation, and hence it is sensitive to slight changes in the position of the major circulation features, the SPCZ and the STHP (Fig. 11.3). For example, the eastern Pacific Hadley cell tends to be stronger during El Niño years, which may result in drier conditions on Rapa Nui, though overall there is no significant long-term correlation between rainfall and the phase of ENSO.

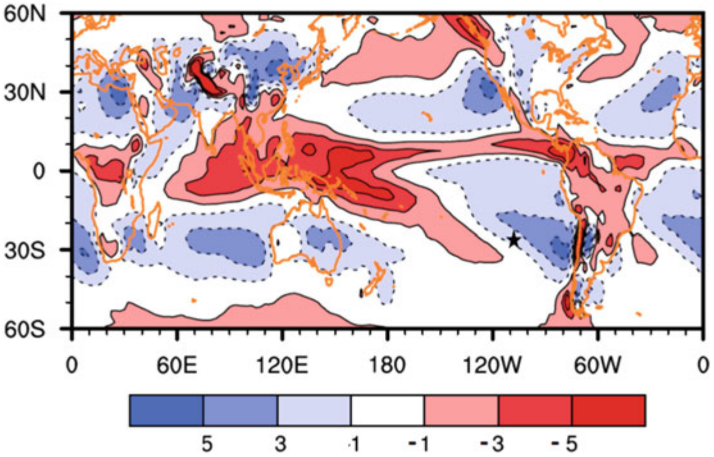


Fig. 11.1 Mean annual 500 hPa vertical velocity (Pa•s^{-1}). Negative values (red) indicate ascending motion. Location of Rapa Nui shown by the red star (from Chen et al. 2014)

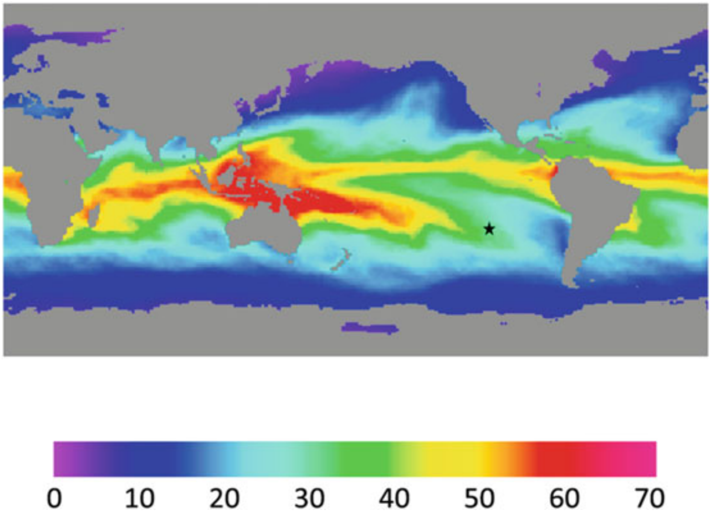


Fig. 11.2 Mean monthly total precipitable water vapor (kg m^{-2}) for 2009. Rapa Nui denoted by the black star. Multi-satellite data from HOAPS (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite) (Mears et al. 2018)

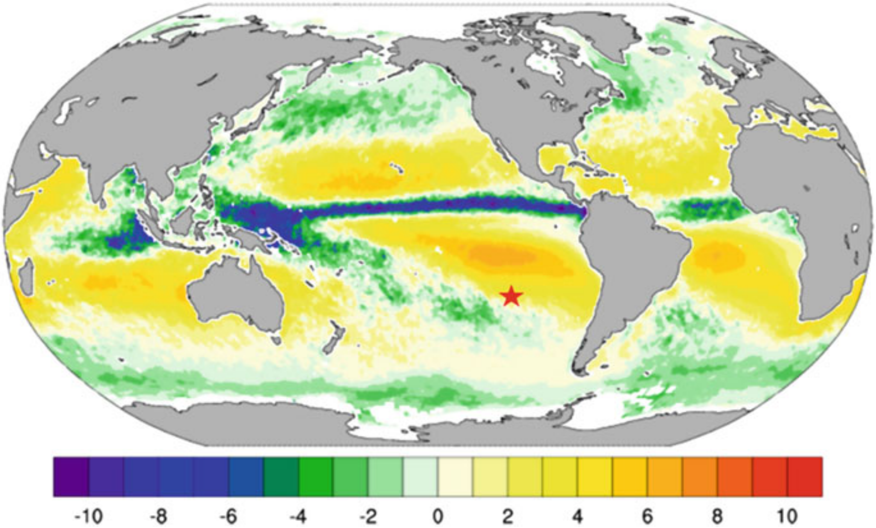


Fig. 11.3 Evaporation minus precipitation (in mm day^{-1}) for 2005, based on HOAPS-3 data (Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite). Variables are derived from SSM/I passive microwave radiometers

3 The Climate of Rapa Nui

Meteorological observations have been recorded in Mataveri (27.1606°S, 109.427°W; 48 m above sea level) since 1955 (for rainfall) and 1970 (for temperature). Figure 11.4 shows daily mean temperatures and daily rainfall totals. Because of the oceanic setting of Rapa Nui, the mean annual temperature has a small seasonal range (~6 °C), from ~24 °C in mid-February to ~18 °C in late July and August.

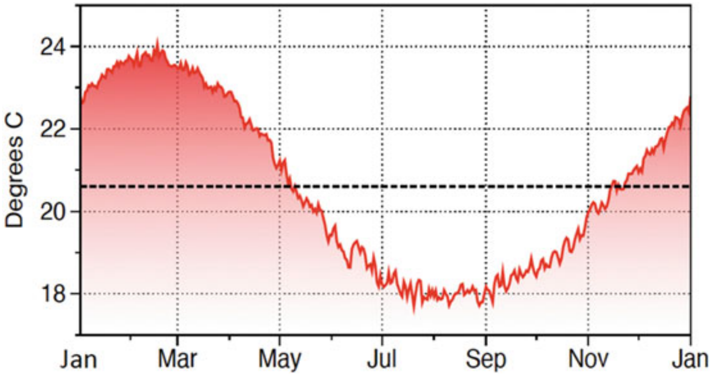


Fig. 11.4 Mean daily temperature at Mataveri, Rapa Nui (27.16° S, 109.43° W) from 1970–2020. Black dashed line is mean annual temperature

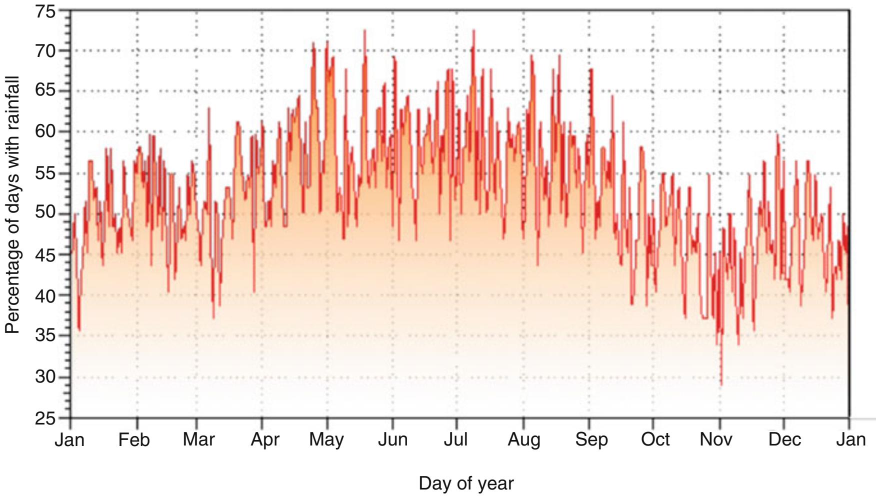


Fig. 11.5 Percentage of days recording rainfall (mean/median = 52; max = 73; min = 27)

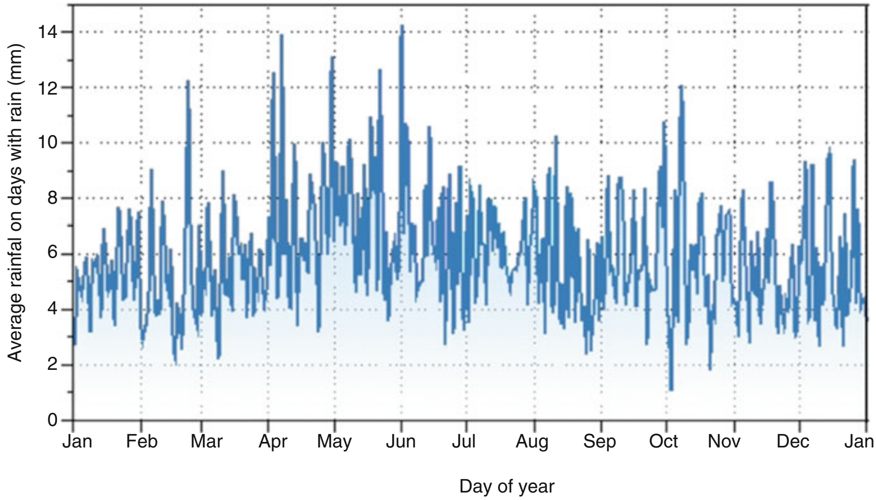


Fig. 11.6 Mean daily rainfall amount on days with rain (June 1954 to June 2018). Rainfall totals averaged ~1109 mm per year (1955–2019); 42% of annual rainfall is recorded in the months of April–July

Rainfall is quite common, and the probability of it raining on any day of the year is 52%, with maximum probabilities from April to August (Fig. 11.5). Of course, that does not mean rainfall occurs continuously on rainy days; using satellite data, Trenberth and Zhang (2018) estimate that, on average, in the region of Rapa Nui it rains for just a few hours on those days, reflecting the convective nature of most rainfall events. Daily totals on rainy days, are generally low (Fig. 11.6;

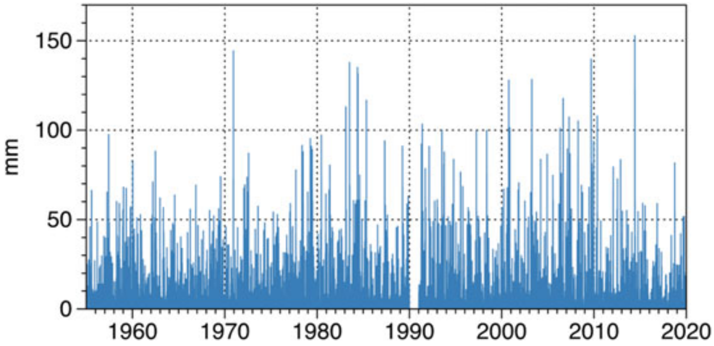


Fig. 11.7 Daily total rainfall amounts (mm) since 1955; data were not recorded in 1990

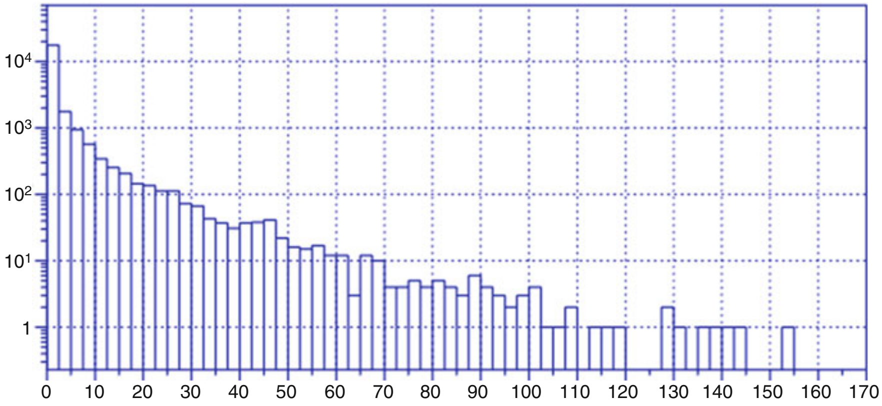


Fig. 11.8 Histogram of daily rainfall amounts (log scale on y-axis); max daily amount: 153 mm

median = 5.9 mm) with highest daily rainfall totals from early April to mid-June; the maximum daily rainfall amount ever recorded was 153 mm on June 3, 2014, accounting for 15% of that year's annual total rainfall, but in general daily rainfall totals in excess of 100 mm are quite rare (Figs. 11.7 and 11.8). An examination of the rainfall distribution in wet years compared to dry years shows that the difference is mainly due to a higher frequency of occasional days with particularly heavy rainfall (Steiger et al. 2022). For example, in the wettest year on record (1979: 1928 mm of annual rainfall) there were 15 days with daily rainfall amounts >25 mm compared to only 2 days in 2017 (which had only 662 mm in total, the second driest year on record) (Fig. 11.9). Back trajectory air mass analysis for anomalously wet and dry years shows very little difference in the source of moisture, with the prevailing trajectory from the southern Pacific Ocean to the southwest of Rapa Nui bringing moisture to the island (Fig. 11.10).

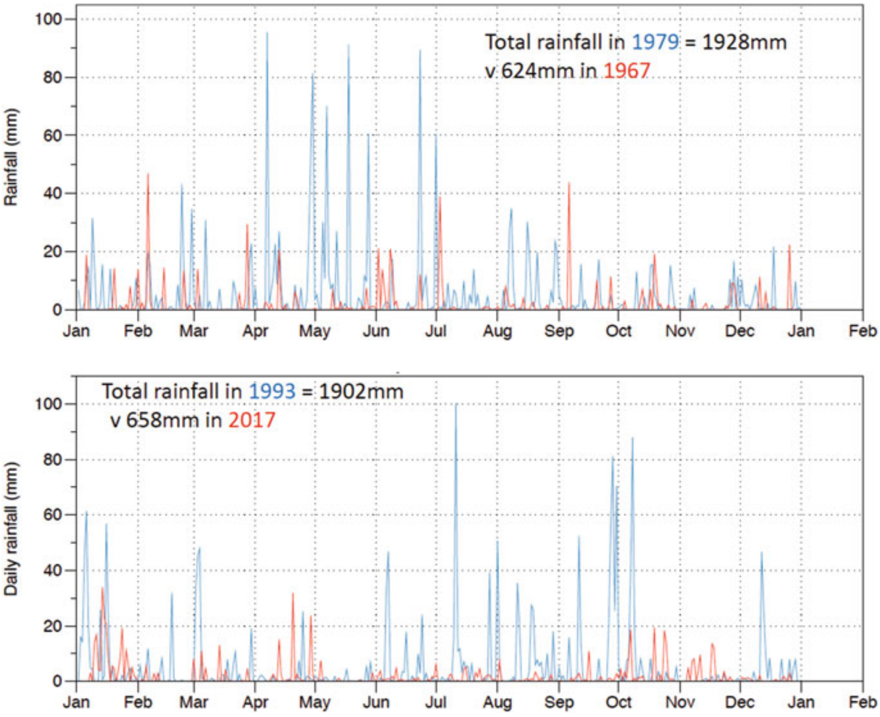


Fig. 11.9 Daily rainfall distributions in the two wettest years, 1979 and 1993 (blue), compared to two of the driest years, 1967 and 2017 (red)

4 Interannual Variations

Over the past 50 years, mean annual temperatures have varied little from year to year (with an overall range of <2 °C) but temperatures were consistently below average for most of the 1980s and 1990s, and have generally been above average since then (Fig. 11.11). There is a slight tendency for days with high amounts of rainfall to be cooler than average. Seasonal temperatures tend to be lower and rainfall amounts higher during El Niño events (indicated by a positive value of the Multivariate ENSO Index, MEI) and the reverse during La Niña events (Negative MEI), but the relationship is inconsistent and not statistically significant (Figs. 11.12 and 11.13) (cf. Genz and Hunt 2003). This reflects the fact that Rapa Nui is located between the regions where, *on average*, air temperatures are positively correlated with ENSO, and the area where the correlation is negative (Fig. 11.14). In any given year, a slight shift in the circulation will likely determine if there is a positive or negative effect from ENSO on temperature, and so overall the pattern is not consistent.

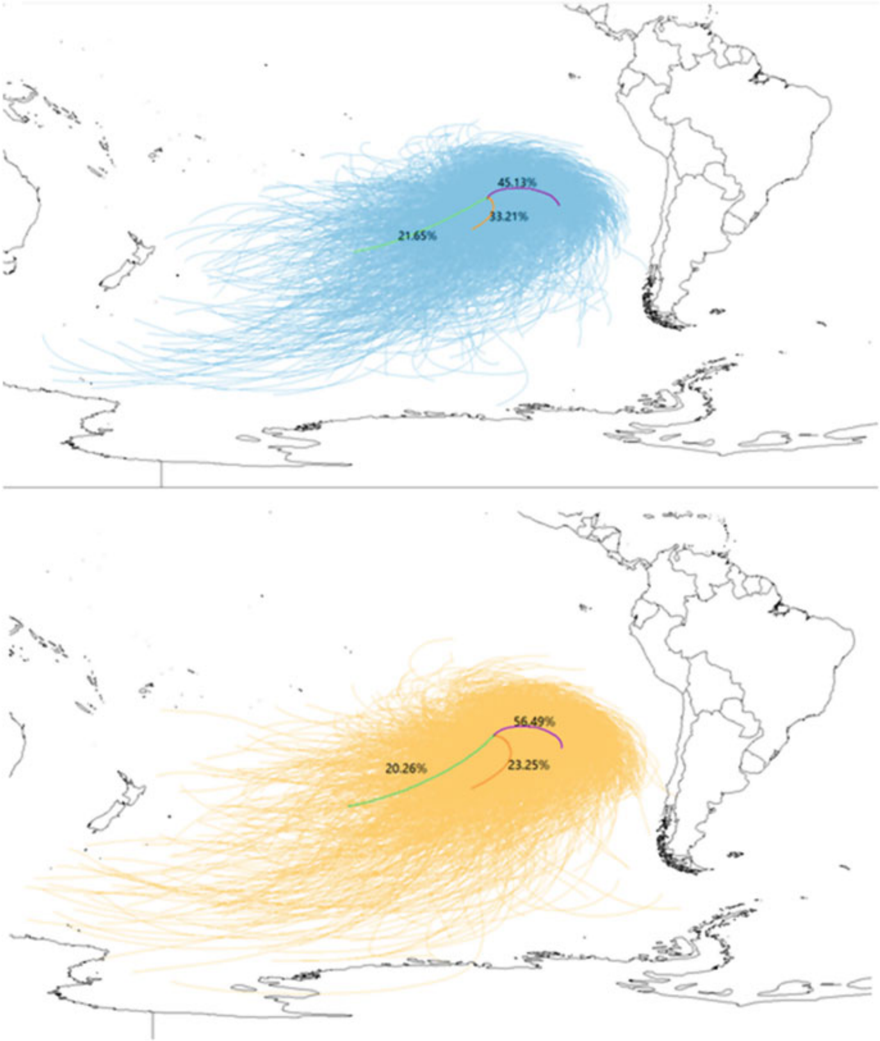


Fig. 11.10 Annual air parcel back-trajectory (96 h) composites for anomalously wet (upper panel) and dry (lower panel) years. Wet years (>1 standard deviation above the mean): 1959, 1962, 1972, 1979, 1983, 1984, 1993, 2000, 2007, 2009. Dry years (>1 standard deviation below the mean): 1956, 1961, 1965, 1966, 1967, 1971, 2010, 2011, 2016, 2017

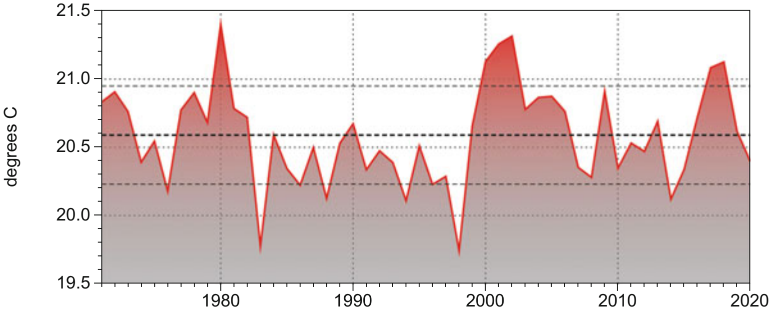


Fig. 11.11 Mean annual temperature at Mataveri, Rapa Nui for the period 1971–2019. The black dashed lines indicate the mean temperature (20.6 °C) ±1 standard deviation (0.36 °C)

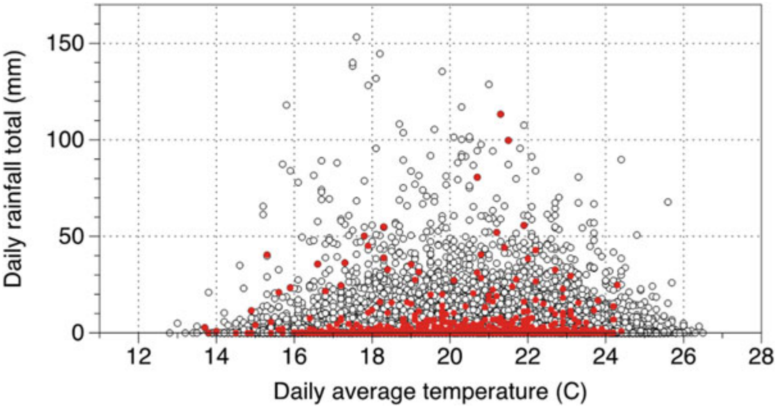
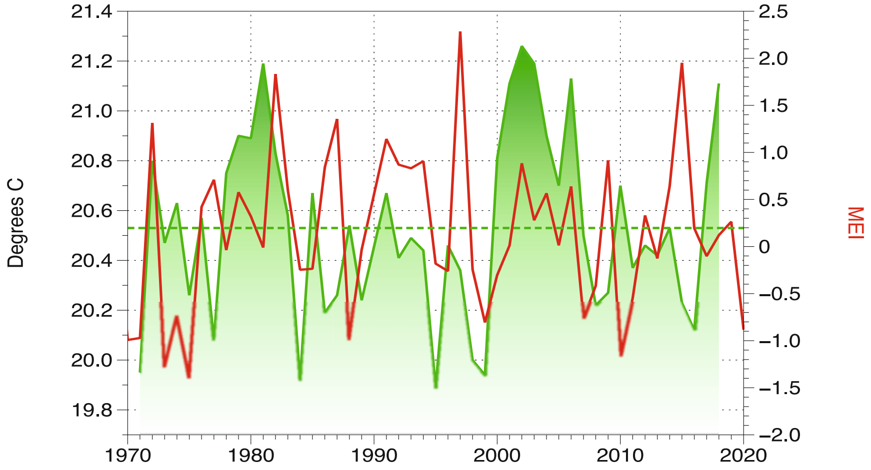


Fig. 11.12 Daily rainfall amounts versus daily temperatures (1971–2018). Red dots indicate rainfall during the years of 1982–1983 (April–March) and 1997–1998 (April–March, which were both strong El Niño events

Rainfall was above average from ~1977 to 2009 but has been consistently below the long-term mean since then. This period of persistently low rainfall over the last decade is unique in the entire instrumental record (Fig. 11.15) and has shifted the water balance of one of the few lakes on the island (Rano Raraku) to the point, where it is currently almost dry (Fig. 11.16). Annual festivities at this crater lake used to include swimming races on reed mats, but that would be impossible today as the lake has very little water left in it. The decline in water level is not the result of increased water use but of the persistent decline in annual rainfall.



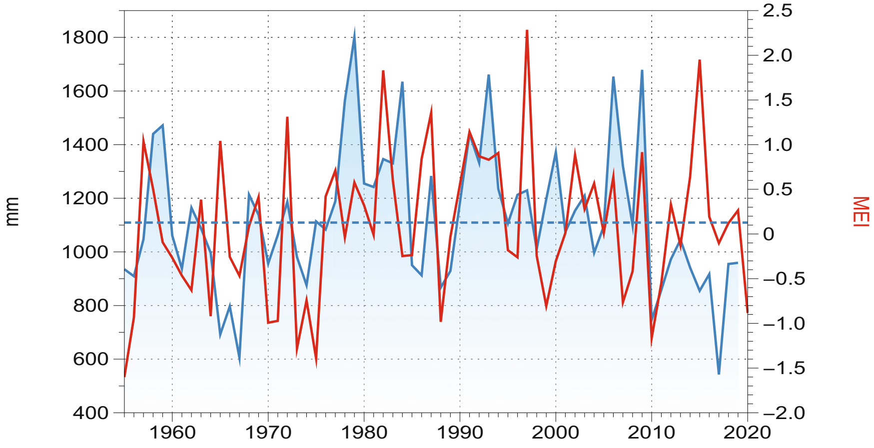


Fig. 11.13 Multi-ENSO index (red) averaged from April–March, compared to April–March annual temperature, 1971–1972 to 2018–2019 (green, above) and annual precipitation totals, 1955–1956 to 2019–2020 (blue, below). The correlation coefficients between the MEI and rainfall, and MEI and temperature are 0.12, and 0.15, respectively (not significant)

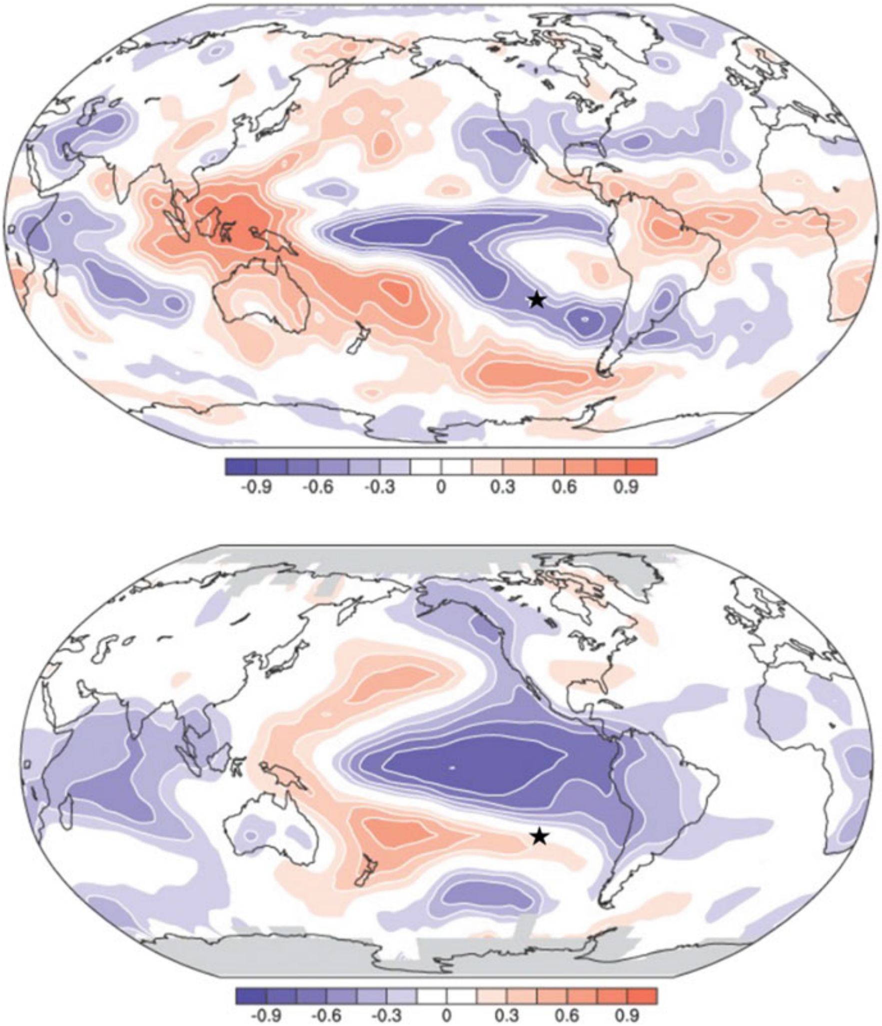


Fig. 11.14 Correlations with the Southern Oscillation Index (SOI) (based on normalized Tahiti minus Darwin sea level pressures), for annual (May to April) surface temperature averages (bottom) for 1958–2004, and GPCP precipitation amounts for 1979–2003 (top). Location of Rapa Nui indicated by a black star (from Trenberth et al. 2007). Negative values of the SOI correspond to El Niño events (positive values of the MEI in Fig. 11.13). Almost identical patterns are found with other indices such as the Multivariate ENSO Index (MEI), and the Tripole Index for the Interdecadal Pacific Oscillation (see Garreaud et al. 2009; Henley et al. 2015)

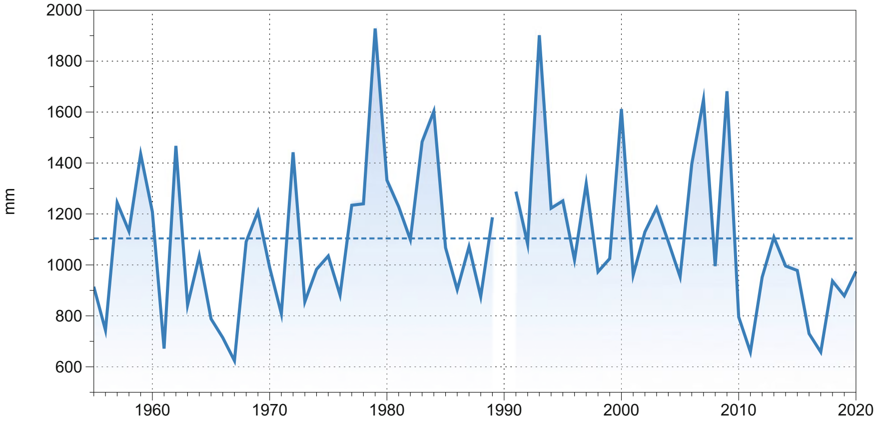


Fig. 11.15 Annual rainfall totals, 1955–2020 (dashed line = long-term average [1104 mm]; median = 1067 mm). Mean annual temperature and rainfall totals are not significantly correlated (r = 0.08). Rainfall has been well below the long-term mean since 2010

There is little evidence that decadal variability of Pacific circulation patterns, such as the Pacific Decadal Oscillation (PDO) and related indices, can account for the changes in rainfall on Rapa Nui. As with ENSO, Rapa Nui is located at the boundary between areas that are strongly linked to such oscillations (Fig. 11.17) and long-term changes in the PDO cannot explain the remarkable decline in rainfall over the past decade (Fig. 11.18). However, this decline may be linked to large-scale changes in atmospheric conditions in the western Equatorial Pacific: as the Warm Pool in that area has expanded, rainfall along the South Pacific Convergence Zone has increased, but east of that convergence, rainfall has declined (Figs. 11.19 and 11.20) (Roxy et al. 2019). This is the opposite of what appears to have happened from 1000 to 1400 CE when the SPCZ was displaced further to the east (Higgins et al. 2020). How future changes in greenhouse gases will affect the Warm Pool and these large-scale circulation features is unclear, but if the recent shift in the SPCZ persists in the future, it is likely that rainfall on the island will remain well below the average recorded during the instrumental period, with serious implications for water availability. Periods of prolonged drought have occurred in the past (Rull 2020), but given the higher population pressures on the island today, from both permanent residents and the much larger number of tourists, persistent drought would likely be much more consequential.

Fig. 11.16 Rano Raraku on March 16th 2018, almost completely dried up (photographs by R.S. Bradley)

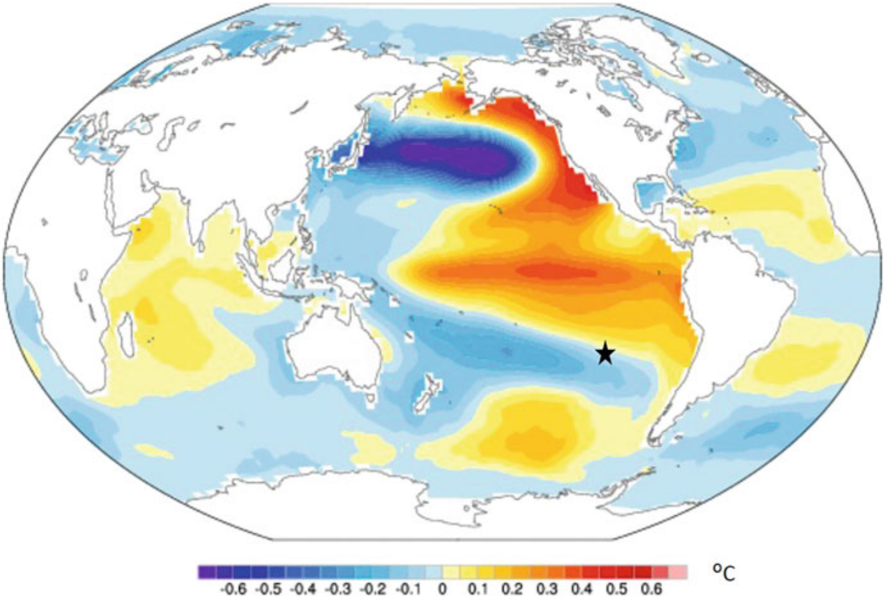


Fig. 11.17 The sea surface temperature anomaly pattern associated with the positive phase of the Pacific Decadal Oscillation (PDO) (cf. Mantua and Hare 2002), using ERSST v.5, from https://psl.noaa.gov/pdo/. Location of Rapa Nui indicated by a black star

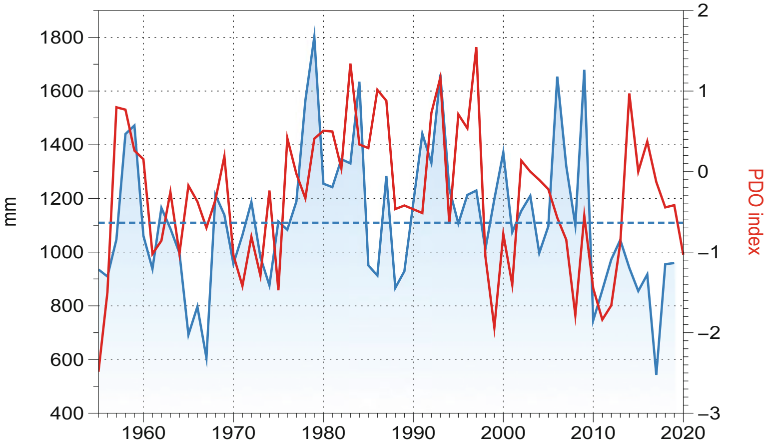


Fig. 11.18 April–March rainfall totals at Mataveri, Rapa Nui (blue) 1955–1956 to 1920–1921, compared to the April–March Pacific Decadal Oscillation Index (red); r = 0.3 (not significant). Mean rainfall total indicated by dashed line. PDO values are from the National Center for Environmental Information, NOAA

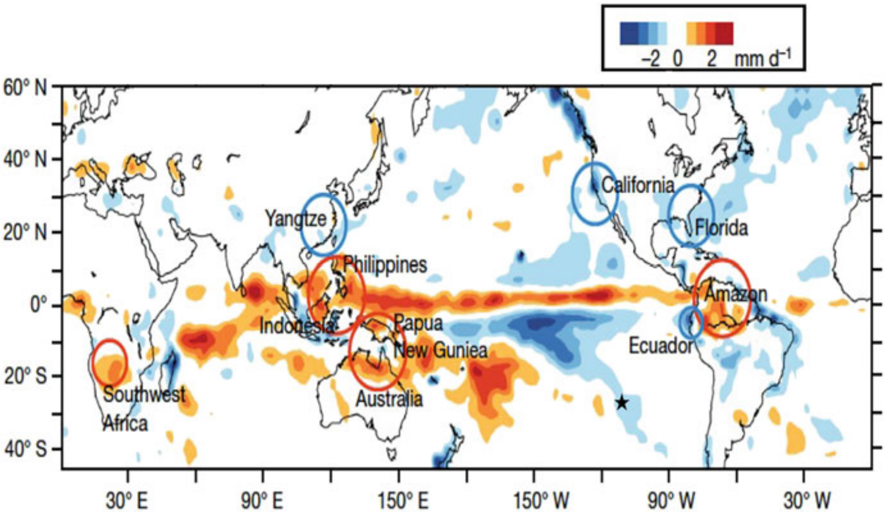


Fig. 11.19 Observed trend in rainfall (mm day^{-1}, per 38 years). As the West Pacific Warm Pool has expanded, rainfall along the South Pacific Convergence Zone has increased, but decreased to the east of it (from Roxy et al. 2019). The position of Rapa Nui is shown by the black star

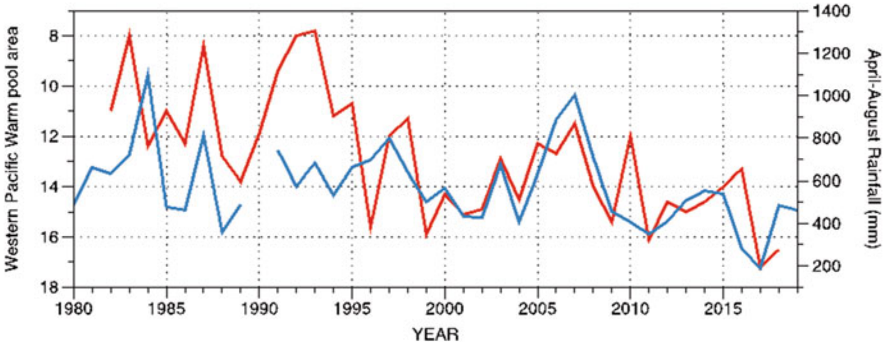


Fig. 11.20 Relationship between April–August rainfall at Rapa Nui (blue) and area of the West Pacific Warm Pool (red: plotted inversely, in 10^6 km^2); ($r = -0.49$). As the Warm Pool has expanded, rainfall in Rapa Nui has declined (Warm Pool area data from Roxy et al. 2019)

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Chapter 12
Prehistoric Paleoecology of Easter Island

Valentí Rull

1 Introduction

Paleoecological knowledge has largely been neglected in the study of Easter Island's prehistory, defined as the time interval between Polynesian settlement (800–1200 CE, common era) and European contact (1722 CE). The initial works of Flenley and coworkers, carried out approximately four decades ago (Flenley and King 1984; Flenley et al. 1991), were taken by many as the final word in Easter Island paleoecology. These pioneering works demonstrated that the island was deforested during the last millennium and that the original palm-dominated forests never recovered. Following an earlier, hitherto unverified, hypothesis of Mulloy (1974), forest clearing was linked by Flenley et al. (1991) to the human overexploitation of natural resources, which would have caused starvation, social conflicts, and wars, leading to the cultural collapse of the prehistoric Polynesian society living on the island (thereafter, the ancient Rapanui society). Bahn and Flenley (1992) considered the socioecological demise of Easter Island as a microcosmic model for the whole planet and warned about current global exploitation practices based on the premise of unlimited growth and human selfishness. The idea of a self-induced cultural collapse, also known as the ecocide theory (Diamond 2005), was considered the paradigm of Easter Island's prehistory and dominated the scene for decades, not only in the scientific arena but also in the press and other popular media. However, a number of issues, such as the deforestation chronology and its spatial patterns across the island as well as the potential influence of climate changes and synergistic climate-human effects on ecological change, remain unclear and require

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_12

further paleoecological research (Rull 2016a; Rull et al. 2013, 2016). In addition, some archaeological evidence suggests that the ancient Rapanui did not experience a prehistoric population demise but remained a healthy society until European contact (Hunt 2006, 2007; Mulrooney 2013; Mieth and Bork 2015, 2017; Stevenson et al. 2015). As a result, the ecocide paradigm was called into question, and the search for a more holistic view that includes the possible influence of climatic changes and/or synergistic climate-human effects was recommended (Rull 2018).

One constant in research on Easter Island, including the pioneering paleoecological works of Flenley and coworkers, has been the idea that the climate remained constant or that small climatic variations were not influential in prehistoric ecological and cultural developments (Flenley et al. 1991). For example, Bahn and Flenley (1992) dismissed a potential influence of climate on deforestation, claiming that it "seems odd that the forest should survive for at least 37,000 years, including the major climatic fluctuations of the last ice age and the postglacial climatic peak, only to succumb to drought after people arrived on the island." These authors therefore concluded that only humans were responsible for forest clearing. The idea of climatic constancy was also extended to other research disciplines (e.g., archaeology, anthropology, ethnography), which adopted it as one more paradigm, a paradigm still in force today.

Shortly after the pioneering paleoecological works of Flenley and his colleagues, some researchers suggested the possibility that climatic changes, especially droughts, were involved in the ecological and cultural collapse on the island (McCall 1993; Haberle and Chepstow-Lusty 2000; Orliac and Orliac 1998; Hunter-Anderson 1998; Nunn 2000; Nunn and Britton 2001). However, most of these proposals were based on climate change records from distant locations (e.g., Australasia, New Zealand, South America) or regional climatic patterns, and in situ evidence of climate shifts on Easter Island remained absent. According to most of these authors, interannual variability in regional climatic mechanisms such as the El Niño-Southern Oscillation (ENSO) could have affected Easter Island's climate during the prehistoric period. However, the possible influence of the ENSO on the island's climatic variability was not universally accepted and remained controversial (MacIntyre 2001; Genz and Hunt 2003; Stenseth and Voje 2009; Caviedes and Waylen 2011).

In the following decades, paleoecological studies intensified, and clear evidence of prehistoric climatic changes on Easter Island was obtained (Mann et al. 2008; Sáez et al. 2009; Cañellas-Boltà et al. 2013; Rull et al. 2015). It was also demonstrated that deforestation was not homogeneous over time and space but, rather, occurred at different times and at different rates across the island (Rull 2020a). In addition, although paleoecology has not provided direct evidence regarding a number of cultural matters on Easter Island, it has furnished empirical information that can aid in understanding processes such as initial discovery (Rull 2019) or the potential role of climate changes and synergistic climate-human effects on significant prehistoric cultural shifts (Rull 2016a, 2020b).

This chapter reviews the paleoecological study of Easter Island's prehistory, with an emphasis on the research developed during the last two decades, which has been particularly overlooked. The chapter begins with a brief section about the cultural chronology of Easter Island, which is needed to place paleoecological discussions in an appropriate temporal context. Then, the paleoecological sites that have been studied to date on the island are briefly described, with an emphasis on sedimentary freshwater bodies and the cores retrieved from them. This is followed by a succinct historical account of paleoecological studies, with an emphasis on the last decade, which has witnessed a significant resurgence of paleoecological work. The most relevant paleoecological findings are summarized and discussed with regard to four main thematic issues: settlement, climatic change, deforestation, and cultural change. Finally, some remarks related to possible future research and the need for interdisciplinary studies aimed at achieving a holistic view of Easter Island's prehistory are provided.

2 Prehistoric Chronology

Traditionally, the prehistory of the island has been subdivided into three main periods, but agreement on the names of these periods and the boundary dates between them has yet to be reached, which hinders the development of a generally accepted chronology (Lipo and Hunt 2016). The different chronological schemes are presented and discussed in more detail in Rull (2020a); here only the main features and disagreement points are summarized.

The arrival of the Polynesian settlers who developed the ancient Rapanui society on the island has been dated to between 800 CE and 1200 CE by different authors (Steadman et al. 1994; Martinsson-Wallin and Crockford 2002; Flenley and Bahn 2003; Hunt and Lipo 2006; Vargas et al. 2006; Kirch 2010; Wilmshurst et al. 2011). There is still no consensus and some authors do not recognize a presence before 1200 CE, which complicates a phased approach.

The settlement phase, also known as the Early Period or *Ahu Moroki*, would have extended until approximately 1200 CE and was likely a phase of adaptation of the Polynesian colonizers to their new environments, linked to cultural activities with a low ecological impact on the landscape (Mieth and Bork 2010). Heyerdahl (1952) contended that the first settlers were not Polynesians but Amerindians (or Native Americans), who arrived on the island by 400 CE but were further eradicated by the Polynesian settlers. However, this author did not provide convincing evidence, and his proposal was deeply questioned by Flenley and Bahn (2003), who defended the notion that Easter Island was colonized only once, from East Polynesia. Recent genomic studies have suggested that the Amerindian influence on ancient Rapanui society can be dated back to pre-Columbian times (1280–1495 CE), although it is not clear whether Native Americans arrived on Easter Island by their own or were brought there by Polynesians after traveling to America (Thorsby 2007, 2016). Repeated pre-Columbian voyages of Polynesian navigators to America between 700 CE and 1350 CE have been supported by consistent evidence from a wide range of disciplines (Jones et al. 2011; Roullier et al. 2013).

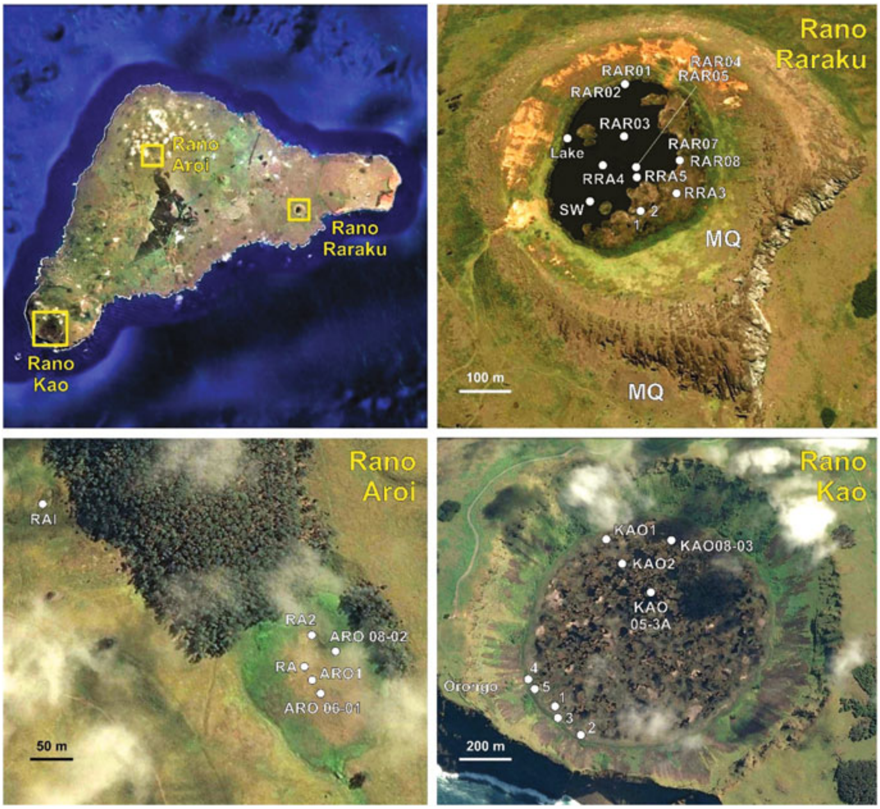

Fig. 12.1 Google Earth images of the paleoecological sites of Easter Island indicating all cores retrieved to date with published results, which constitute the basis for the EIRA radiocarbon database discussed in the text. *MQ, moai* quarry, slopes where most *moai* were carved. Modified from Rull (2016b)

The second period—Middle Period, *Ahu Moai*, or Expansion Phase, also known as Golden Age (Boersema 2015)—would have been the time of a flourishing ancient Rapanui society, characterized by a significant population increase, the development of the *moai* sculpture industry and cult, and the general deforestation of the island. During this phase, the cultural center of Rapanui society was the quarry where the megalithic sculptures, thought to represent clan chiefs (*ariki*), known as *moai*) were carved (Rano Raraku) (Fig. 12.1). The maximum authority of the island, the *Ariki Mau*, was always the chief of the *Miru* clan, considered to be a direct descendant of the first Polynesian settlers. This phase would have ended between 1500 CE and 1680 CE (Smith 1961; Kirch 1984; Flenley and Bahn 2003; Vargas et al. 2006; Nunn 2007; Boersema 2015).

The third phase (Late Period, *Huri Moai*, or Decadent Phase) is thought to have been characterized by the end of the former Rapanui splendor, as manifested in a demographic decline, a deforested island, and a general exhaustion of natural resources, leading to starvation, social conflicts, and wars. Social conflicts among clans would have led to the toppling and breakage of the *moai* and the destruction of the stone altars (*ahu*) where they were erected and emplaced for worship. This would have led to a profound social, religious, and political shift from the ancestor worship (also known as *Moai* Cult) to the Birdman Cult, in which the *Ariki Mau* was no longer a permanent authority selected according to dynastic rules (Robinson and Stevenson 2017). Under the new cult, the maximum authority of the island, the Birdman (*Tangata Manu*), was reselected each year after an athletic competition aimed at obtaining the first egg of the migratory sooty tern (*Onychoprion fuscatus*), considered a symbol of fertility, which nested in the adjacent Motu Nui islet each Austral spring. The Birdman Cult was centered on the ceremonial village of Orongo, situated on the SW crest of Rano Kao (Fig. 12.1), which replaced Rano Raraku as the cultural center of Rapanui society. The end of the third period and of the island's prehistory was marked by the arrival of the first European explorers, in 1722 CE, but the ancient Rapanui culture continued, as reflected in the archaeological record.

This classical three-stage chronology has largely been influenced by the ecocide paradigm, as manifested in the purported occurrence of a profound social crisis and a demographic crash due to the depletion of natural resources, which characterized the transition between the second and third periods. The situation would have been different under a scenario of resilience of the ancient Rapanui society to island deforestation. The widespread use of protected stone structures for cultivation (*manavai*) and the use of novel methods to minimize evaporation and temperature fluctuations (lithic mulching) would have allowed the continuity of the Rapanui population with no significant declines (Stevenson et al. 1999, 2015; Wozniak 1999, 2001, 2017; Mulrooney 2013; Mieth and Bork 2015, 2017; Jarman et al. 2017). Regarding the shift from the ancestor worship to the Birdman Cult, some authors have suggested that this was a postcontact characteristic (Robinson and Stevenson 2017). In addition, some historians suggest that *moai* toppling might have occurred after European contact, as a result of the exacerbation of rivalry among the Rapanui clans competing for the position of Birdman (Fischer 2005). Historical records also show that the true cultural collapse of Rapanui society and culture occurred long after initial European contact and actually took the form of a genocide (Peiser 2005; Hunt 2006, 2007). Indeed, slavery practices and the introduction of epidemic diseases hitherto unknown by the Rapanui (syphilis, smallpox, tuberculosis) led to a population collapse that reduced the population of 3000–4000 people reported by the first European visitors to barely 110 individuals in 1877 (Pinart 1878). In addition, by 1868, the whole population of the island—approximately 800 people by that time—had been Christianized and therefore acculturated.

In summary, a robust chronology of prehistoric human developments on Easter Island remains to be defined. According to Lipo and Hunt (2016), the most precise information available concerns the timing of Polynesian settlement—which these authors place at 1220–1260 CE (Hunt and Lipo 2006)—and the arrival of Europeans, in 1722. The interval between these two dates can only be defined as "the past," with little more precision than that (Lipo and Hunt 2016). Based on the above discussion, a tentative chronology might be represented by a continuum defined by the following processes, with loose and sometimes overlapping boundaries: deforestation (800–1200 CE to 1450–1650 CE), *Moai* Cult or ancestral worship (1200 CE to 1600–1650 CE), Birdman Cult (1600–1850 CE), moai toppling (1770s–1830s CE), and the genocide (1860s–1870s CE).

3 Paleoecological Archives

Easter Island includes only three freshwater bodies with sediments suitable for paleoecological research: Rano Aroi, Rano Kao, and Rano Raraku (Fig. 12.1). Other archives that may contain paleoecological evidence include soils and archaeological sites, which are widespread across the island. In marine environments, corals are potential paleoecological archives that have been poorly exploited to date and deserve further consideration.

3.1 Sedimentary Basins

Rano Aroi is a swamp/mire of 150 m in diameter located at a 430 m elevation near the Terevaka summit (Fig. 12.1). Its water level is controlled by groundwater inputs subject to the influence of seasonal variations in precipitation and human extraction through the construction of an artificial outlet in the 1960s (Herrera and Custodio 2008). The aquatic vegetation is dominated by *Scirpus californicus*, *Polygonum acuminatum*, and ferns of the genera *Asplenium*, *Vittaria*, and *Cyclosorus*, whereas the surrounding area is covered by grasslands and a small *Eucalyptus* forest planted during the 1960s (Zizka 1991). The mire infilling is predominantly peat and is at least 16 m deep in the center, which may correspond to an age of approximately 70,000 yr BP (extrapolated age) (Margalef et al. 2013, 2014).

Rano Kao contains the largest lake of the island, with a diameter of 1250 m, located at a 110 m elevation. This lake is very peculiar, as its surface is a mosaic of water and aquatic vegetation taking the form of floating mats up to 3–4 m deep overlying the water column, which is approximately 10 m deep near the center. This configuration determines the existence of two different paleoecological archives: the superficial floating peaty mat and the more clastic bottom lake sediments accumulated below the water column. The floating mats are dominated by the characteristic semiaquatic species of the island, *Scirpus californicus* and *Polygonum acuminatum*, together with another sedge, *Pycreus polystachyos* (Zizka 1991). The oldest ages recorded so far in the floating mat correspond to the last millennium (Gossen 2007; Horrocks et al. 2013). A significant number of archaeological sites have been found within and around the Kao crater, including the ancient village of Orongo, formed by stone houses, which is one of the more important and well-preserved archaeological complexes of the island (Robinson and Stevenson 2017). The maximum depth of the lake sediments recorded thus far is approximately 21 m (but it is supposed to be deeper, as hard rock has not been reached), and the maximum age is 34,000 cal yr BP (Gossen 2007, 2011; Horrocks et al. 2013).

Rano Raraku contains a small and shallow lake of 300 m in diameter and 2–3 m in depth, located at an 80 m elevation. Hydrologically, the lake is closed, with no surface outlet, and is used by humans as a freshwater source for consumption. The main water inputs are rainfall and catchment runoff (Herrera and Custodio 2008). The water level is influenced by periodic water extraction, and the maximum depth recorded in modern times is approximately 3 m (Sáez et al. 2009); however, in some years, the lake may be totally dry. The aquatic vegetation is dominated by *Scirpus californicus*, which forms a more or less continuous floating belt (partly rooted in lake sediments) along the east margin of the lake, where the input of terrigenous materials from the catchment is greater and more continuous. Rano Raraku is one of the most emblematic sites of the island, as it was the quarry where the *moai* were carved. Many of these stone statues, some of which are unfinished, remain on the east side of the crater, where most of the *moai* were carved. The sedimentary infilling is at least 14 m deep in the center of the lake, which corresponds to an age of 34,000 cal yr BP (Sáez et al. 2009).

Cores from the Aroi, Kao, and Raraku sediments have been retrieved from different parts of these craters using a variety of coring equipment and extrusion techniques. Figure 12.1 shows the location of all cores obtained to date and Table 12.1 displays the main features of each core and the main paleoclimatic and paleoecological proxies studied. The EIRA (Easter Island Radiocarbon Ages) database, which includes all radiocarbon dates obtained in these sediments (Rull 2016b), is publicly available at the NOAA Paleo Data website (www.ncdc.noaa.gov/paleo-search/study/19805).

3.2 *Other Archives*

In addition to lake and swamp sediments, other paleoecological archives have been investigated on Easter Island, although less intensively. A coral paleoclimatic record covering only the second half of the twentieth century is available, although the authors of the study providing these data estimate that Easter Island's corals have the potential to span at least 250 years and possibly 400 years (Mucciarone and Dunbar 2003). The study of soil profiles and selected materials from some archaeological sites has also provided paleoecological information, mainly on the nature of the ancient forests and deforestation timing. In several of these archives, Mann et al. (2003) and Mieth and Bork (2005, 2010, 2015, 2017) found evidence of slash and burn activity, agroforestry, forest clearing and regeneration, soil erosion, and other ecological processes. In other dryland soils and archaeological sites, Horrocks and Wozniak (2008) and Horrocks et al. (2016) found evidence of forest clearing and the cultivation of Polynesian crops. At some archaeological sites, Orliac (2000) and

Table 12.1 Characteristics of radiocarbon-dated peat and lake sediment cores obtained in Easter Island, according to the original references. The main proxies studied in each core are also indicated. ND No Data. Publication lag refers to the years elapsed between coring and the first detailed publication of the original results

Core	Water depth (m)	Core length (m)	Year	Coring device	Main proxies studied	References
Rano Aroi (27° 05’ 37.37” N – 109° 22’ 26.50”; 433 m elevation)						
ARO1	0.00	~11.50	1977	Russian	Lithostratigraphy, elemental analysis, pollen and spores, charcoal	Flenley (1979), Flenley and King (1984), Flenley et al. (1991)
ARO 06–01	0.00	13.90	2006	UWITEC	Facies description, mineralogy, elemental analysis, stable isotops, plant and animal macrofossils,pollen and spores	Margalef et al. (2014), Margalef et al. (2013, 2014)
ARO 08–02	0.00	4.00	2008	Russian	Facies description, mineralogy, elemental analysis, stable isotops, plant and animal macrofossils, pollen and spores	Margalef (2014), Margalef et al. (2013, 2014), Rull et al. (2015)
RA2	0.00	8.00	1997	Livingstone	Lithostratigraphy, diffuse spectral reflectance, pollen and spores	Peteet et al. (2003)
RA	0.00	4.00	2009	Russian	Lithostratigraphy, magnetic susceptibility, plant and animal macrofossils, charcoal, pollen and spores, biosilicates, phytoliths, starch	Horrocks et al. (2015)
RAI[a]	0.00	2.11	2009	Russian	Lithostratigraphy, magnetic susceptibility, plant and animal macrofossils, charcoal, pollen and spores, biosilicates, starch	Horrocks et al. (2015)
Rano Kao (27° 11′ 12.57” N – 109° 26′ 06.75”; 107 m elevation)						
KAO1	0.00	~11.00	1977	Russian	Lithostratigraphy, elemental analysis, pollen and spores, charcoal	Flenley (1979), Flenley and King (1984), Flenley et al. (1991)
1	ND	20.00	2009	Russian + Livingstone	Lithostratigraphy, magnetic susceptibility, plant and animal macrofossils, charcoal, pollen and spores, starch	Horrocks et al. (2013)

3	ND	~5.00	2009	Russian + Livingstone	Lithostratigraphy, phytoliths, pollen and spores, starch	Horrocks et al. (2012b)
2	ND	~6.00	2009	Russian + Livingstone	Lithostratigraphy, phytoliths, pollen and spores, starch	Horrocks et al. (2012b)
4	ND	~12.00	2009	Russian + Livingstone	Lithostratigraphy, phytoliths, pollen and spores, starch	Horrocks et al. (2012b)
5	ND	~7.00	2009	Russian + Livingstone	Lithostratigraphy, phytoliths, pollen and spores, starch	Horrocks et al. (2012b)
KAO2	10.50	20.85	1983	Russian	Lithostratigraphy, elemental analysis, pollen and spores, charcoal	Butler and Flenley (2001), Butler and Flenley (2010), Butler et al. (2004), Flenley (1996)
KAO3 (KAO05-3A)	10.50	21.50	2005	Russian + Livingstone	Magnetic susceptibility, oxygen isotopes, pollen and spores	Gossen (2007, 2011)
KAO08-03	ND	2.20	2008	Russian	Lithostratigraphy, pollen and spores, charcoal, non-pollen palynomorphs (NPP)	Rull et al. (2018), Seco et al. (2019)
Rano Raraku (27° 07′ 19.79” – 109° 17′ 20.66”; 80 m elevation)						
RRA3	0.00	~12.00	1977	Russian	Lithostratigraphy, elemental analysis, pollen and spores, charcoal	Flenley (1979), Flenley and King (1984), Flenley et al. (1991)
RRA4	2.80	~17.20	1983	Russian	Lithostratigraphy, mineralogy, elemental analysis	Flenley et al. (1991)
RRA5	ND	13.40	2005	Livingstone	Pollen and spores	Azizi and Flenley (2008)
SW	2.00	~3.40	1990	Piston	Magnetic properties, plant and animal microfossils (pollen, cladocera, ostracoda, diatoms), pigments	Dumont et al. (1998)
1	6.00	~1.00	1998	Gravity	Lithostratigraphy, magnetic susceptibility, organic matter, charcoal, pollen and spores	Mann et al. (2003, 2008)
2	6.00	~1.00	1998	Gravity	Organic matter	Mann et al. (2003, 2008)
RAR01	ND	~5.70	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy	Sáez et al. (2009)

(continued)

Table 12.1 (continued)

Core	Water depth (m)	Core length (m)	Year	Coring device	Main proxies studied	References
RAR02	ND	~6.80	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy	Sáez et al. (2009)
RAR03	ND	~13.80	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy, plant and animal macrofossils, pollen and spores	Sáez et al. (2009), Cañellas-Bolta (2014), Cañellas-Boltà et al. (2012, 2014, 2016)
RAR04	ND	~6.00	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy	Sáez et al. (2009)
RAR05	ND	~13.20	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy	Sáez et al. (2009)
RAR07	ND	~12.80	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy, plant and animal macrofossils, pollen and spores	Sáez et al. (2009), Cañellas-Bolta (2014), Cañellas-Boltà et al. (2012, 2014, 2016)
RAR08	ND	~12.60	2006	UWITEC	Magnetic susceptibility, facies description, elemental analysis, mineralogy	Sáez et al. (2009), Cañellas-Bolta (2014), Cañellas-Boltà et al. (2013)
Lake	2.60	2.25	2009	Livingstone	Lithostratigraphy, plant macrofossils, pollen and spores, phytoliths, starch	Horrocks et al. (2012a)

[a] Rano Aroi Iti (see Fig. 12.1)

Orliac and Orliac (1998) identified woody plant taxa from charcoal fragments. The usual proxies utilized in the study of soils and archaeological sites have been soil stratigraphy, with an emphasis on carbon layers, charred wood/endocarp and palm root casts, charred wood, pollen, phytoliths, and starch remains.

4 Historical Development of Paleoecological Studies

Paleoecological studies on Easter Island have their origin in some undated cores retrieved in the mid-twentieth century by Thor Heyerdahl, which were analyzed for pollen by Olof Selling, but the results remained unpublished. The only information available is a personal communication from Selling to Heyerdahl, suggesting that the island was probably forested at some time in the past (Heyerdahl and Ferdon 1961). These forests must have disappeared before European contact, as the first Europeans to arrive found a treeless island (Fischer 2005). The idea of a forested island had previously been proposed, albeit without empirical evidence, in the late eighteenth century by La Pérouse (1797), who also speculated that the ancient Rapanui would have cut down all the trees, making the island inhabitable. Mulloy (1974, 1979) related the initial palynological evidence to his own findings identifying palm root molds associated with carbonized wood in ancient soils, which were interpreted as remnants of former palm forests. In a paper written in 1976 but not published until two decades later, Mulloy (1997) emphasized the need for repeating and extending the paleobotanical studies initiated by Selling to test the hypothesis of a formerly forested island. From this point onward, the sediments of the suitable sites (Rano Aroi, Rano Kao, and Rano Raraku) began to be systematically cored and dated. However, the historical development of these studies was a discontinuous process due to the occurrence of a hiatus of approximately 10 years (1993–2004) characterized by a significant reduction in paleoecological research activity, which separated the more active pioneer (1977–1992) and revival (2005–present) phases (Fig. 12.2). A detailed account of the analyses performed, the interpretation of the obtained results, and the conclusions that were drawn is available from Rull (2020a); here, only a summary will be provided.

4.1 The Pioneer Phase

The first systematic paleoecological studies based on dated sediments were performed by a single research team led by the palynologist John Flenley. All the work developed during this phase was based on the analysis of pollen and other proxies from cores obtained between 1977 and 1983 in Rano Aroi, Rano Kao, and Rano Raraku and was published between 1979 and 1992 (Flenley 1979; Dransfield et al. 1984; Flenley and King 1984; Flenley et al. 1991; Bahn and Flenley 1992). The synthesis of all these works constituted the first general paleoenvironmental and

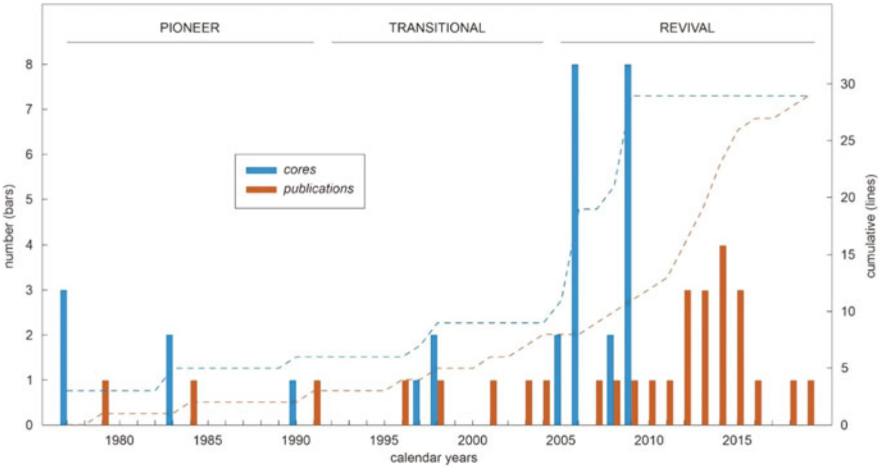

Fig. 12.2 Number of cores retrieved on Easter Island for paleoecological study and publications derived from these cores during the last four decades (1977–2019). Only publications with original data (Table 3.1) for the cores are considered, and reviews are excluded. Bars represent the actual number of cores and papers (left scale), and dotted lines are the cumulative trends (right scale)

paleoecological reconstruction for Easter Island, which was summarized by Flenley et al. (1991) in a graphical synthesis (Fig. 12.3). The same authors synthesized their findings into five main conclusions (Flenley et al. 1991):

1. Easter Island was formerly forested, and the main trees included an unknown palm, *Sophora toromiro*, and *Triumfetta semitriloba*.
2. The uppermost altitudinal limit of this forest probably consisted of a shrub belt dominated by *Coprosma* and an unknown Compositae-Tubuliflorae species. This upper boundary was located near the elevation of Rano Aroi (430 m) but oscillated in response to climatic changes.
3. The climate of Easter Island fluctuated between 38,000 and 26,000 ^{14}C yr BP. Between 26,000 and 12,000 ^{14}C yr BP, the climate was probably cooler and drier than in the present. The magnitude of this cooling would have been 2 °C or less compared to present average temperatures. A precipitation (or moisture balance) increase occurred beginning at 10,000 ^{14}C yr BP. The uppermost forest limit increased in elevation at this time, which suggested a coeval rise in temperature.
4. Anthropogenic forest clearance took place between 1200 and 800 ^{14}C yr BP (ca. 900 and 1260 CE), and the total demise of the forest occurred at 500 ^{14}C yr BP (ca. 1450 CE), which is compatible with the hypothesis that the decline of the megalithic culture was associated with deforestation.
5. The hypothesis that Easter Island is poor in woody species due to its isolation is not supported by these results, which are more compatible with the view that human activities were responsible for the present-day floristic depauperation.

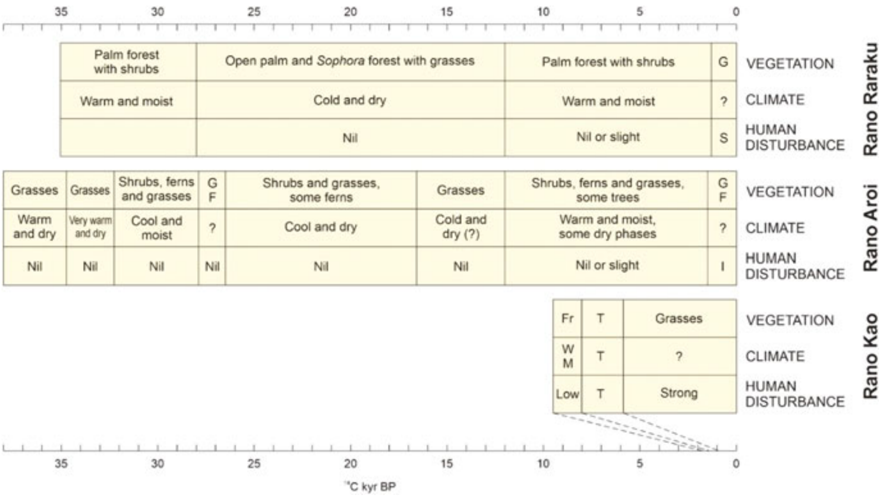

Fig. 12.3 Summary of the general conclusions of Flenley et al. (1991) regarding vegetation, climate, and human disturbance at the three coring sites studied. *G* Grasses, *F* Ferns, *Fr* Forest, *I* Increasing, *M* Moist, *S* Slight, *T* Transition, *W* Warm. Redrawn and modified from Flenley et al. (1991)

The pioneering paleoecological work developed by Flenley and his coworkers on Easter Island seemed to strongly support the ecocide hypothesis explicitly proposed some decades before by Mulloy (1974). Regarding a potential role for climatic change in this ecological and cultural demise on the island, Bahn and Flenley (1992) considered it implausible that forests that had survived major climatic fluctuations such as the last ice age and postglacial warming perished because of the occurrence of a drought just after island colonization by humans. For these authors, such a coincidence was difficult to believe. A year later, Bahn and Flenley (1992) published the first sociecological synthesis for the island, based on the chronology of the Rano Kao palynological record and the archaeological, ethnographical, anthropological, and historical evidence available at that time. These authors suggested that in addition to its religious motivations, the *moai* sculpture industry was a strongly competitive activity among clans aimed at producing the largest and most spectacular monuments. The *moai* workers were dedicated exclusively to this task and should have been maintained by other sectors of society dedicated to food production. As *moai* activity increased, food producers had to support ever-increasing numbers of nonfood producers, which led to deforestation and vegetation depletion by burning and cutting, leaching and soil erosion, increasing evaporation, and, ultimately, decreasing crop yields. This would have also caused the drying up of springs and streams. At the same time, the disappearance of large timber for canoe building eventually led to the abandonment of deep-sea fishing and prevented the islanders from navigating to other islands.

In agreement with Mulloy (1974), these authors considered the communal compulsion of the ancient Rapanui to produce giant statues and platforms “insane,” to the point that basic subsistence activities such as farming and fishing were neglected. Bahn and Flenley (1992) considered Easter Island to be a microcosm model for the whole planet, as both are isolated systems and have limited resources. Therefore, Easter Island may be viewed as a real experiment regarding the consequences of the overexploitation of natural resources, from which we can extract important lessons for the future of the Earth. However, Bahn and Flenley (1992) identified some obstacles to achieving this goal. One is the selfishness inherent to human nature, which prioritizes our own short-term goals rather than general social interests, and the other is the current attachment to unlimited growth, which ignores the preservation of natural resources for future generations.

4.2 The Transitional Phase

After the consolidation of the collapse theory by pioneering studies, paleoecological research on Easter Island experienced a hiatus of approximately a decade, which is referred to as the transitional phase here. This phase was characterized by sporadic, nonsystematic coring and the publication of only a few papers, which did not introduce significant modifications to the collapse paradigm. During this phase, paleoecological chronology research took a step backward, as most coring campaigns produced chronologically inconsistent sequences with frequent sedimentary gaps and age inversions, which prevented the development of reliable age-depth models. This was the case for Rano Kao (Flenley 1998), Rano Aroi (Peteet et al. 2003), and Rano Raraku (Dumont et al. 1998).

The occurrence of age inversions within radiocarbon dating depth sequences was attributed to the contamination of younger sediments with older carbon from different sources. After a detailed analysis of radiocarbon dates in a newly obtained sedimentary sequence from Rano Kao, Butler et al. (2004) concluded that it was not possible to draw conclusions about the ecological history of the island due to significant chronological inconsistencies. These authors recommended the development of additional coring activities and new chronologies after the careful selection of the materials to be dated. A new core with similar dating problems was obtained in Rano Raraku by Dumont et al. (1998). After the analysis of planktonic organisms from the most recent sediments, these authors suggested that Amerindians from the Inca Empire would have arrived on Easter Island by 1300–1450 CE and may have contributed to cultural collapse by halting the tradition of *moai* carving.

The most informative paleoecological reconstruction carried out during the transitional phase was performed by Mann et al. (2003), combining island-wide edaphic studies and a new sedimentary sequence from Rano Raraku. An island-wide analysis of buried primeval soils—i.e., those that supported former forests—revealed that general deforestation likely occurred between 1200 and 1650 CE,

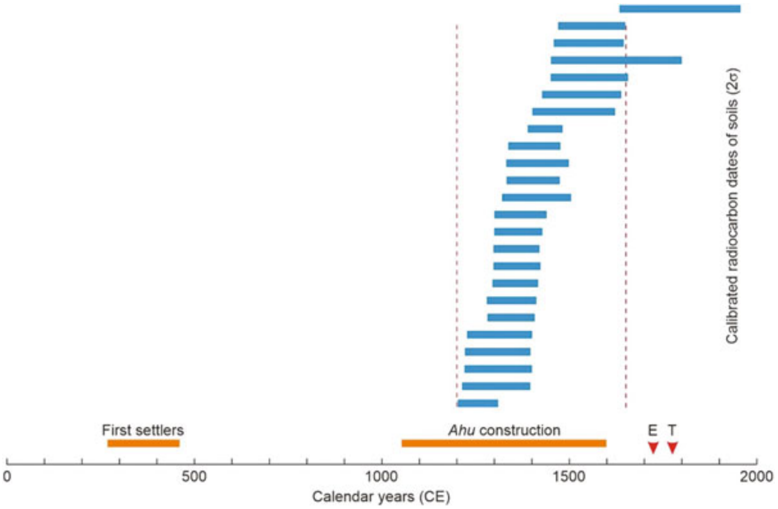

Fig. 12.4 Calibrated radiocarbon ages of charcoal from soils overlying the primeval forest soils (blue bars) and the main prehistorical events (orange bars and red arrows). E European contact, T *moai* toppling. Redrawn and simplified from Mann et al. (2003)

coinciding with the phase of megalithic statue construction (Fig. 12.4). This was supported by the study of a new core obtained in Rano Raraku, where evidence for major forest burning and soil erosion was recorded from 1070 to 1280 CE. Mann et al. (2003) noted that this occurred long after the initial human settlement of the island and suggested that the island might have been occupied, perhaps transiently, by Polynesian hunter-gatherers thriving on its rocky shores. Permanent settlement, dryland farming, and population growth might have been initiated by 1200 CE, leading to the ecological transformation of the island.

Orliac (2000) and Orliac and Orliac (1998) analyzed charred pieces of wood from some archaeological sites and identified a number of woody taxa from the fourteenth to seventeenth centuries. A number of these taxa are no longer present on the island, and it was speculated that they might have been components of the ancient forests, or trees/shrubs cultivated temporarily by the prehistoric Rapanui, or driftwood used for fire. Cummings (1998) performed the first phytolith and starch analyses on Easter Island and realized that the preservation of these proxies at archaeological sites was good enough to provide information on deforestation and Rapanui cultivation practices.

4.3 The Revival Phase

The revival phase can be subdivided into two well-differentiated parts. The first part extended between 2005 and 2010 and was characterized by a significant increase in coring activities and the reanalysis of previously obtained cores. The second part (2012–present) was marked by the publication of the analyses performed on the cores obtained between 2005 and 2009.

4.3.1 Coring Intensification and Reanalysis

During the first part of the revival phase, a total of 20 cores were retrieved, almost half (9) of which were from Rano Raraku, while seven were from Rano Kao, and four were obtained in Rano Aroi (Table 12.1). Some preliminary results from these cores (Azizi and Flenley 2008; Gossen 2007; Sáez et al. 2009) along with some reanalyses of older cores (Mann et al. 2008; Butler and Flenley 2010) were published during the same time interval. All of these papers were related to Rano Raraku and Rano Kao (Fig. 12.1). Using the Rano Raraku core of Mann et al. (2003), the same authors identified a sedimentary gap of more than 3000 years—4090–4410 cal yr BP to 660–770 cal yr BP (1180–1290 CE)—that was attributed to a climatic drought or a series of droughts, causing lake to dry up (Mann et al. 2008). This drought was attributed to a latitudinal shift in the subtropical storm track, which controls the intensity and frequency of cyclonic storms on Easter Island. This was the first local, independent evidence of prehistoric climate change on Easter Island. Pollen analysis of the same core documented abrupt forest clearing by 1200 CE, in accord with previous edaphic studies by the same authors (Mann et al. 2003) (Fig. 12.4). The deforestation of the Raraku catchment was not linked to the drought mentioned above, as the decline of palms and a coeval charcoal increase, interpreted as evidence of anthropogenic forest burning, occurred after the sedimentary gap.

The occurrence of an extensive depositional gap across Rano Raraku sediments was confirmed by a further systematic study based on a N-S transect of new cores retrieved in 2006 (Table 12.1), combined with those from older studies (Sáez et al. 2009). This hiatus extended between approximately 5888–4200 cal yr BP and 550–850 cal yr BP (1100–1450 CE) and was related to the mid-Holocene aridity crisis documented elsewhere in the circum-Pacific area. According to Sáez et al. (2009), this extended drought would have been caused by an insolation minimum, leading to the weakening of the summer monsoon, or in agreement with Mann et al. (2008), the southern shift of storm tracks forced by El Niño-like dominant conditions in the South Pacific.

In 2005, the first core with a chronologically coherent age-depth model, obtained using *Scirpus californicus* (totora) seeds as dating material, was retrieved in Rano Kao (Gossen 2007, 2011). Preliminary sedimentological analyses of this core suggested a sudden increase in soil erosion, possibly linked to deforestation, by 650–720 CE. Further pollen analyses were carried out to confirm this fact, but to the knowledge of the author, this work remains unpublished. Butler and Flenley (2010) resumed the analysis of their problematic Rano Kao core using totora seeds as dating material and obtained a more consistent age-depth model. Pollen analysis revealed the occurrence of two main deforestation events associated with conspicuous charcoal increases. The first event (50–100 CE) occurred long before the hitherto accepted Polynesian settlement of the island, and the origin of the fires involved was considered to be problematic. The second event (1350–1800 CE) was chronologically consistent with human deforestation by fire. For Butler and Flenley (2010), the most interesting feature of this core was the possibility that human disturbance began approximately 100 CE and continued thereafter, possibly varying in intensity but never ceasing. However, according to these authors, this interpretation would contradict most archaeological reconstructions, and more research was needed for a sound assessment.

Soil investigations have also provided relevant information on Easter Island's prehistory during the first part of the revival phase. Using the density and distribution of palm root casts in primeval soils across the island, Mieth and Bork (2010) estimated that approximately 16 million palm trees had once grown on the island, covering approximately 70% of its surface. The same authors later extended their estimate to 20 million palms, covering 80% of the island (Mieth and Bork 2015, 2017). The radiocarbon dating of soil charcoal at different points on the island yielded dates of 1200 CE and 1500 CE for the beginning and the end, respectively, of intensive slash and burn practices across the island. The lack of evidence for extensive and intensive palm fruit eating by rats led these authors to conclude that the island-wide forest clearing was exclusively human-caused. As in the case of Butler and Flenley (2010), robust evidence of forest regeneration (i.e., the occurrence of two generations of root casts) after fire was found in soil profiles (Mieth and Bork 2010).

4.3.2 Publication Resurgence

During the second part of the revival phase, the renewed coring efforts of the 2005–2009 period began to bear fruit in the form of papers reconstructing the main paleoecological trends of the last millennia, mainly through pollen analysis but also based on a variety of physicochemical proxies that provided independent evidence for climatic and environmental change. This phase has been subdivided into two main categories according to the aims of the corresponding paleoecological studies. The first category encompasses studies based on biological analyses (pollen, phytoliths, starch, diatoms, arthropods) of cores from the three craters and an island-wide soil survey focused mainly on the reconstruction of prehistoric cropping activity. The second category includes multiproxy (physical, chemical, and biological) studies on continuous, mostly gap-free, cores from the same waterbodies, aimed at reconstructing the spatiotemporal deforestation patterns and their potential climatic and/or anthropogenic drivers.

Horrocks et al. (2012b) studied several cores retrieved along the SW margin of Rano Kao, just below the ceremonial village of Orongo (Fig. 12.1), the center of the Birdman Cult. The obtained results suggested terracing for gardening and dwelling within the crater. The radiocarbon dating of the four cores retrieved (albeit using totora fruit/seeds) again showed frequent age inversions, which prevented the development of a reliable chronology. The obtained results were consistent

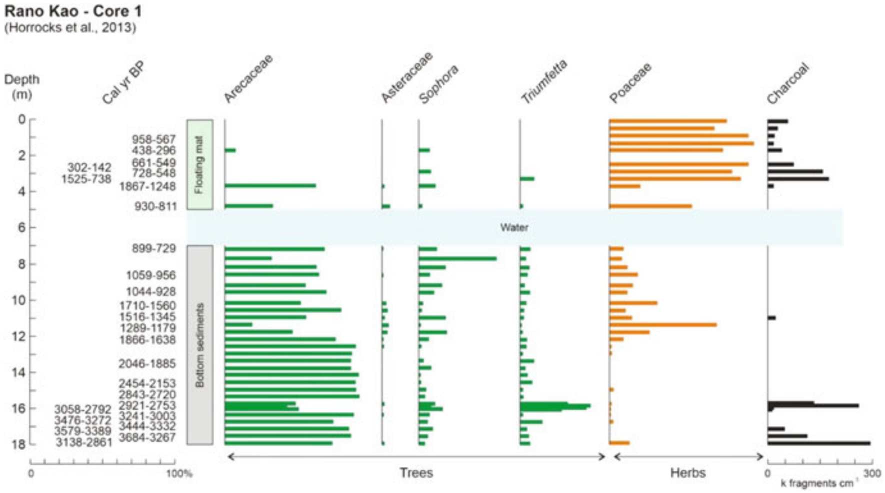

Fig. 12.5 Pollen percentage diagram for the Late Holocene from Rano Kao core 1 (Fig. 12.1, Table 12.1). Only dates obtained from totora seeds/fruits are indicated. Redrawn and simplified from Horrocks et al. (2013)

with a mixed-crop production system including common Polynesian cultigens such as paper mulberry (*Broussonetia papyrifera*), taro (*Colocasia esculenta*), yam (*Dioscorea alata*), sweet potato (*Ipomoea batatas*), bottle gourd (*Lagenaria siceraria*), and banana (*Musa* sp.). This study demonstrated that the SW margin of Lake Kao was an actively cultivated area during and after its deforestation, likely favored by the continuous availability of water and protection from the dominant winds. One of the obtained cores showed a chronologically consistent sequence between approximately 3500 and 1000 cal yr BP (1550 BCE and 950 CE). Microfossil analysis of this interval revealed the occurrence of three events of forest clearing by burning and cultivation (notably banana) between 1730 and 930 BCE, 1110 and 800 BCE, and 660 and 770 CE (Fig. 12.5). The authors considered the third of these events to be chronologically consistent with Polynesian settlement, but the other two events occurred long before that time, and the authors discussed the possibility of contamination by older carbon from different sources.

In Rano Raraku, Horrocks et al. (2012a) found evidence of forest clearing and the appearance of cultivated plants such as taro and sweet potato by 1320–1440 CE. These authors concluded that the Raraku catchment and its surroundings were used not only as a *moai* quarry but also as an extensive multicropping site and suggested that the crater was intensively gardened and terraced, possibly during the peak of the *moai*-quarrying period. Horrocks et al. (2015) also obtained cores from Rano Aroi, and although the age-depth model was poorly constrained between approximately 12,000 and 1000 cal yr BP (950 CE), the results for the last millennium were chronologically coherent and suitable for paleoecological study. Anthropogenic deforestation by burning occurred between approximately

1150–1300 CE and 1520–1770 CE, and the first signs of human occupation and agricultural activity (banana, paper mulberry) were recorded between 1670 and 1740 CE, which was later than in the lower sites (Kao, Raraku). The absence of sweet potato is noteworthy. Another relevant finding was the consistent presence of *Sisyrinchium*, an invasive American weed, since at least 410–630 CE.

The study of prehistoric agricultural activities using microfossils was completed with an extensive survey of dryland soils across the island, carried out by Horrocks et al. (2016). Only one of the soil profiles studied was dated, but the general stratigraphic similarity suggested to the authors that all of the profiles corresponded to times after Polynesian settlement. Microfossil analyses similar to those developed in lake cores allowed the identification of the same cultivated plants recorded in lake terraces, showing no cultivation specialization between lake shores and dryland soils. The most widespread species were paper mulberry, taro, and sweet potato.

The second category of paleoecological studies were focused on the multi-proxy analysis of continuous and chronologically coherent (i.e., free from large sedimentary gaps and age inversions) records of the last millennia, which were able to provide independent paleoclimatic and paleoecological reconstructions, thus avoiding circularity. Three cores encompassing continuous records of this type were obtained in Rano Raraku, Rano Aroi, and Rano Kao (Fig. 12.6).

In the Rano Raraku core, two smaller sedimentary gaps were detected, between approximately 500 CE and 1165 CE and between 1570 CE and 1720 CE, which were interpreted as a consequence of climatic droughts that resulted in the total drying out of the lake (Cañellas-Boltà et al. 2013). The first drought ended during the Medieval Climate Anomaly (MCA), and the second occurred during the Little Ice Age (LIA). The pollen record showed that deforestation did not occur in an abrupt manner but during three main pulses, with no signs of forest regeneration between them (Fig. 12.7). The first deforestation pulse (450 BCE) coincided with the first appearance of the Neotropical weed *Verbena litoralis* and the first increase in charcoal, which suggested an early Amerindian presence (likely

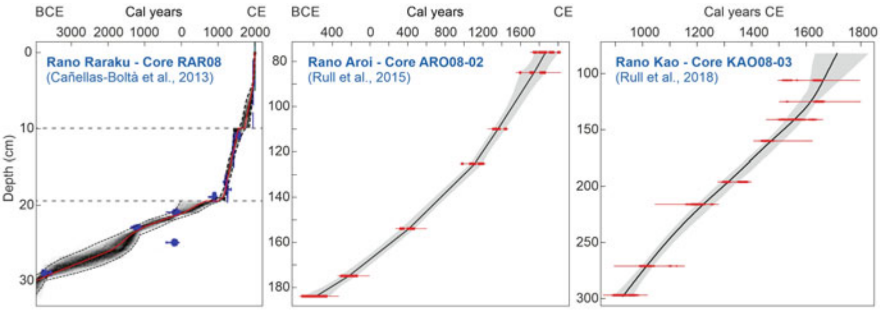

Fig. 12.6 Age-depth models of the continuous and chronologically coherent sedimentary records of the last millennia recovered in Rano Raraku, Rano Aroi, and Rano Kao. The dotted lines in the Raraku model at approximately 10 cm and 20 cm indicate minor sedimentary gaps (see text for explanation). Redrawn and modified from Rull (2020b)

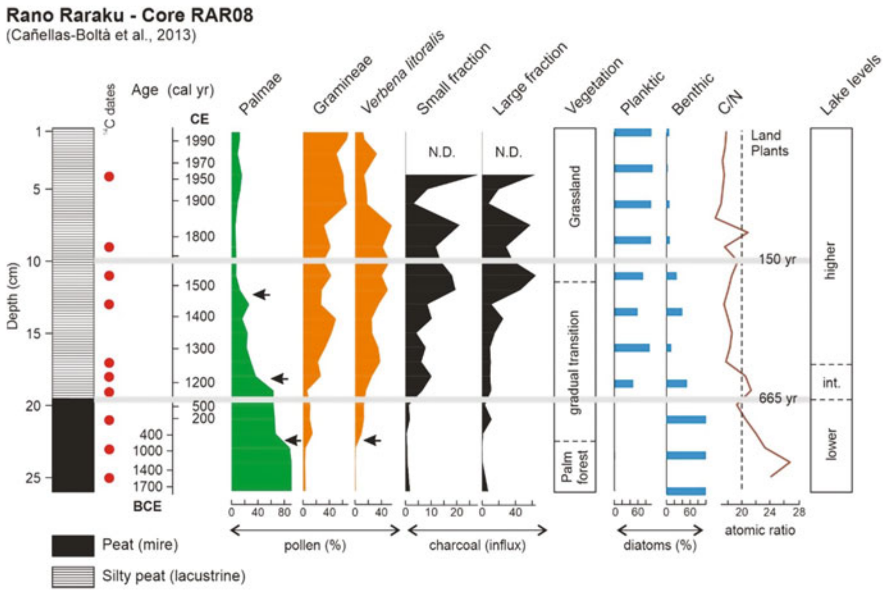

Fig. 12.7 Summary diagram of the last 3700 years as represented in core RAR08 from Rano Raraku (Fig. 12.1, Table 12.1). Sedimentary gaps are represented as gray bands, indicating the years lacking in each case. Black arrows indicate remarkable events discussed in the text. *N.D.* no data. Redrawn and modified from Cañellas-Boltà et al. (2013)

in small populations) on the island approximately one millennium and a half before Polynesian settlement (Cañellas-Boltà et al. 2013). This deforestation event occurred when the catchment was occupied by a mire, as indicated by lithology and diatom assemblages, suggesting the existence of climates that were dry but not as arid as during the MCA and LIA droughts. The second deforestation pulse (1200 CE) was the most intense and was coeval with an outstanding expansion of grass meadows and verbena populations, and an abrupt exacerbation of fires. These changes coincided with increasing lake levels, as recorded by diatoms, suggesting wetter climates after the MCA drought (Fig. 12.7). The acceleration of fire and forest clearing in such wetter climates suggested that humans were been the main driver responsible for these landscape changes. The third forest-clearing event (1475 CE) corresponded to the total deforestation of the Raraku catchment and the irreversible establishment of grass meadows, which was also associated with a significant increase in charcoal. Among the three forest declines, only the second could possibly be linked to climate change, as it occurred immediately after the MCA drought, which could have increased forest flammability, thus acting synergistically with anthropogenic burning (Cañellas-Boltà et al. 2013). After the LIA drought, the diatom assemblages suggested maximum lake levels and, hence, the wettest climates of the last 3700 years.

The Rano Aroi core recorded a long period of constant vegetation, consisting of open palm woodlands within a landscape dominated by grass meadows, between 750 BCE and 1250 CE (Rull et al. 2015). However, some minor variations in palm and grass density between 300 BCE and 50 CE and between 600 CE and 1100 CE coincided with significant reversals in geochemical records (C and N isotopes), indicating the occurrence of drier (but not arid) climates. The second dry phase coincided with the MCA drought reported at Rano Raraku (Cañellas-Boltà et al. 2013). After 1250 CE, a progressive densification of palm woodland to more closed forests took place, coinciding with the appearance of aquatic vegetation, indicating an increase in the water table that was likely due to a wetter climate, which would have favored forest growth. These dense forests were abruptly removed within a century (1520 CE to 1620 CE), coinciding with the first appearance of charcoal, which suggested anthropogenic burning (Rull et al. 2015). The geochemical proxies were consistent with a third dry phase similar to the first two between 1520 CE and 1700 CE, coinciding with the LIA drought documented at Rano Raraku (Cañellas-Boltà et al. 2013).

The Rano Kao record began at approximately 1000 CE, when the catchment was covered by open palm woodlands, which suggested that forests were already being disturbed (Seco et al. 2019). The further deforestation of Rano Kao was gradual but spiked with three pulses of acceleration at approximately 1070 CE, 1410 CE, and 1600 CE, followed by further regeneration trends except after the third pulse, which was irreversible. The first pulse occurred during the MCA drought, which suggested a potential influence of climate. The second pulse (1410 CE) coincided with a small charcoal peak and the first continuous appearance of coprophilous fungi, notably *Sporormiella*, suggesting the onset of continuous anthropogenic disturbance. Palms almost disappeared but slightly recovered until the third declining pulse (1600 CE), when charcoal and *Sporormiella* dramatically increased, roughly coinciding with the first phases of the LIA drought, which could have contributed to fire exacerbation. Seco et al. (2019) suggested that humans were present in the Rano Kao catchment from the beginning of the record but in dispersed or occasional populations. Human presence became more or less permanent by 1410 CE but remained sparse. The catchment was fully deforested and disturbed by larger human populations by 1600 CE. At the same time, the pollen of Apiaceae (likely *Apium*) species increased abruptly and remained constant until at least 1700 CE, which suggested the cultivation of these plants around the lake.

5 Contributions of Paleoecology to the Reconstruction of Easter Island's Prehistory

This section summarizes the usefulness of the paleoecological knowledge described above for a more holistic understanding of Easter Island's prehistory. The discussion is focused on the following aspects: (i) the possibility of the early discovery and/or settlement of the island before Polynesian colonization; (ii) the climatic changes that occurred during the last millennium that could have affected the island's ecology and society; (iii) the spatiotemporal deforestation patterns and their possible natural and anthropogenic drivers; and (iv) the possible influence of climatic droughts on prehistoric cultural aspects, with an emphasis on the shift from the ancestor worship to the Birdman Cult.

5.1 Discovery and Settlement

The first well-dated evidence of deforestation and meadow expansion associated with a fire event, which was suggestive of human disturbance, was found in Rano Kao sediments between 50 CE and 100 CE (Butler and Flenley 2010). The authors noted that this would be contrary to most archaeological reconstructions and discussed other possibilities for the origin of fire, such as spontaneous combustion, a combination of lightning and dry climates, and volcanic eruptions. However, Butler and Flenley (2010) noted that charcoal concentrations never returned to background levels after the 50–100 CE exacerbation, suggesting continuous rather than episodic disturbance. The conclusion was that this evidence should not be dismissed, but further studies would be needed for a sound interpretation in terms of human influence. This conclusion, however, has been maintained by the same authors several years after (Flenley and Butler 2018).

In Rano Kao, Horrocks et al. (2013) found a high concentration of charcoal fragments associated with banana phytoliths in sediments corresponding to 1730–910 BCE. According to these authors, this could be interpreted in terms of anthropogenic forest clearing by fire and associated agriculture, but the dates were confusing, as they were much older than the expected settlement of eastern Polynesia (Kirch 2010; Wilmshurst et al. 2011). Horrocks et al. (2013) did not dismiss the possible existence of dating problems due to contamination, but they maintained the robustness of their age-depth model.

In Rano Raraku, the coincidence of forest clearing with a charcoal increase and the first appearance of the Neotropical weed *Verbena litoralis* suggested that some Amerindian culture could have discovered Easter Island by 450 BCE (Cañellas-Boltà et al. 2013). The disturbance caused was minimal and was compatible with the presence of small scattered ephemeral or intermittent human populations, as previously suggested by Mann et al. (2003).

In Rano Aroi, Horrocks et al. (2015) reported the presence of *Sisyrinchium*, another American invader taxon, since at least 410–630 CE. These authors were very cautious and stated that "... we report this evidence and note that there is no clear reason to dismiss it, nor there is a clear case to accept it. Specifically, we are unaware of any Rapa Nui archaeological excavations or other evidence that provide conclusive support for prehistoric Amerindian presence." However, the case of *Sisyrinchium* is compatible with that of *Verbena* regarding the possible early Amerindian presence on Easter Island.

The absence of archaeological evidence for these early discoveries could be explained by the phenomenon of "evidence clearing" (Rull 2020a), according to which erosion, rising sea levels, and/or further colonizers may destroy or hide the meager terrestrial evidence left by scarce and scattered populations (Stevenson et al. 2000; Flenley and Bahn 2011). Paleoecological evidence contained in lake/swamp sediments, however, is less susceptible to clearing and can provide evidence that is absent in the archaeological record, as has been documented on other oceanic islands (e.g., Rull et al. 2017). The paleoecological findings summarized above could represent the first steps toward obtaining robust evidence of human presence on Easter Island before Polynesian settlement and cannot be neglected, as they are based on robust age-depth models and reliable taxonomic identification. However, the situation can be improved by the incorporation of direct evidence of human presence obtained using biomarkers such as DNA and specific fecal lipids, among others (e.g., Bull et al. 2002; D'Anjou et al. 2012; Hofreiter et al. 2012; Rawlence et al. 2014; Parducci et al. 2017). The field of biomarker analysis in lake sediments is currently in full swing, and it is hoped that future paleoecological studies on Easter Island can take advantage of this.

5.2 Climatic Changes

Paleoecological research on Easter Island has also provided local paleoclimatic information using biotic and abiotic proxies. To date, only changes in the moisture balance have been recorded, notably, the occurrence of two centennial-scale droughts separated by a phase of wet climates (Fig. 12.8). The MCA drought was recorded in Rano Raraku between 500 and 1170 CE, when the lake dried out and remained in that condition for more than six centuries (Cañellas-Boltà et al. 2013). The same event was recorded in Rano Aroi between 600 and 1100 CE (Rull et al. 2015), but in this case, the moisture reduction was less intense, likely due to the higher humidity of the highlands compared to the lowlands (Puleston et al. 2017). This MCA drought was coeval with the Classic Maya Collapse (ca. 900 CE) in Central America, which was attributed to a series of prolonged droughts that led to the ultimate demise of this civilization (Haug et al. 2003). An ensuing moisture increase was recorded between approximately 1100–1170 and 1520–1570 CE in both Rano Raraku and Rano Aroi (Cañellas-Boltà et al. 2013; Rull et al. 2015). The LIA drought occurred between 1570 and 1720 CE, when Lake Raraku dried out again (Fig. 12.8). In Rano Aroi, this drought was more difficult to detect due to the masking effects of human disturbance from 1520 CE onward. The LIA drought coincided with the so-called seventeenth century crisis in tropical Asia, characterized by droughts, famines, and large-scale economic and political disruption (Grove and Adamson 2018). Before the intense MCA and LIA droughts, the climates were drier than at present (but not arid) in both Raraku and Aroi (Cañellas-Boltà et al. 2013; Rull et al. 2015). After the LIA drought, Lake Raraku reached its present-day levels, which suggested the return of wetter climates. These

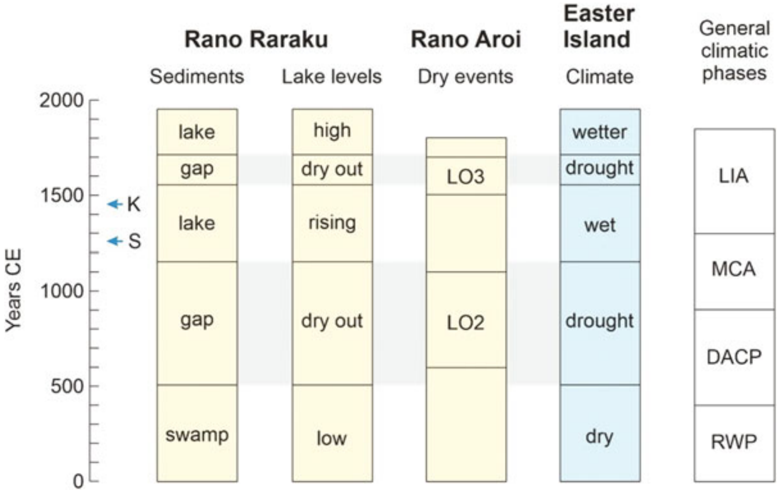

Fig. 12.8 Reconstructed climatic trends of the last two millennia at Rano Raraku and Rano Aroi. Raw data from Cañellas-Boltà et al. (2013) and Rull et al. (2015). Droughts are highlighted with a gray band. Blue arrows indicate regional volcanic eruptions that occurred during Easter Island's prehistory (K—Kuwae eruption, S—Samalas eruption) (Margalef et al. 2018). *DACP* Dark Ages Cold Period, *LIA* Little Ice Age, *MCA* Medieval Climate Anomaly, *RWP* Roman Warm Period

climatic trends have recently been supported by additional geochemical records from Rano Aroi (Roman et al. 2021).

The potential climatic mechanism causing the MCA and LIA droughts can be summarized as a southern shift of the humid subtropical storm track and the emplacement of the dry South Pacific Anticyclone over Easter Island, likely forced by ENSO fluctuations (Mann et al. 2008; Sáez et al. 2009). A potential role for volcanic eruptions occurring in the Pacific Islands has also been discussed, but it is still too soon for a definite answer (Margalef et al. 2018). The most remarkable eruptions of the last millennia corresponded to the Samalas (1257 CE) and Kuwae volcanoes (1453 CE)—located on Lombock Island, near Bali, and the Melanesian Vanuatu Archipelago, respectively—both of which occurred during the Easter Island humid phase between the MCA and LIA droughts (Fig. 12.8). There is still much work to do to achieve a sound understanding of the recent paleoclimatology of Easter Island, especially in terms of resolution and spatial patterns. At present, the Rano Kao core utilized above to reconstruct deforestation trends (Seco et al. 2019) is being studied for high-resolution paleoclimatic reconstruction using the isotopic composition of plant leaf waxes as a precipitation proxy. Other organic biomarkers are available (Eglington and Eglington 2008; Castañeda and Schouten 2011; Maloney et al. 2019; Sear et al. 2020) and should be tested on Easter Island for a more complete paleoclimatic reconstruction.

5.3 Spatiotemporal Deforestation Patterns

Paleoecological records have shown that the deforestation of Easter Island was heterogeneous in time and space, as forest clearing occurred at different times and different rates across the island (Fig. 12.9). The first deforestation event of the last millennium occurred in Rano Kao by 1050 CE, during the MCA drought, and was probably caused by synergistic climate-human effects (Seco et al. 2019). At that time, the Rano Raraku forests and the Rano Aroi open woodlands were still untouched. The next forest clearing event occurred in Rano Raraku at approximately 1200 CE, immediately after the MCA drought, under moderate but sustained fire pressure (Cañellas-Boltà et al. (2013). The occurrence of wetter climates that are more favorable for forest growth (Fig. 12.8) suggests that this deforestation pulse was of anthropogenic origin. Forest retreat was continuous although fires did not increase significantly, which suggests the existence of positive feedback amplifying

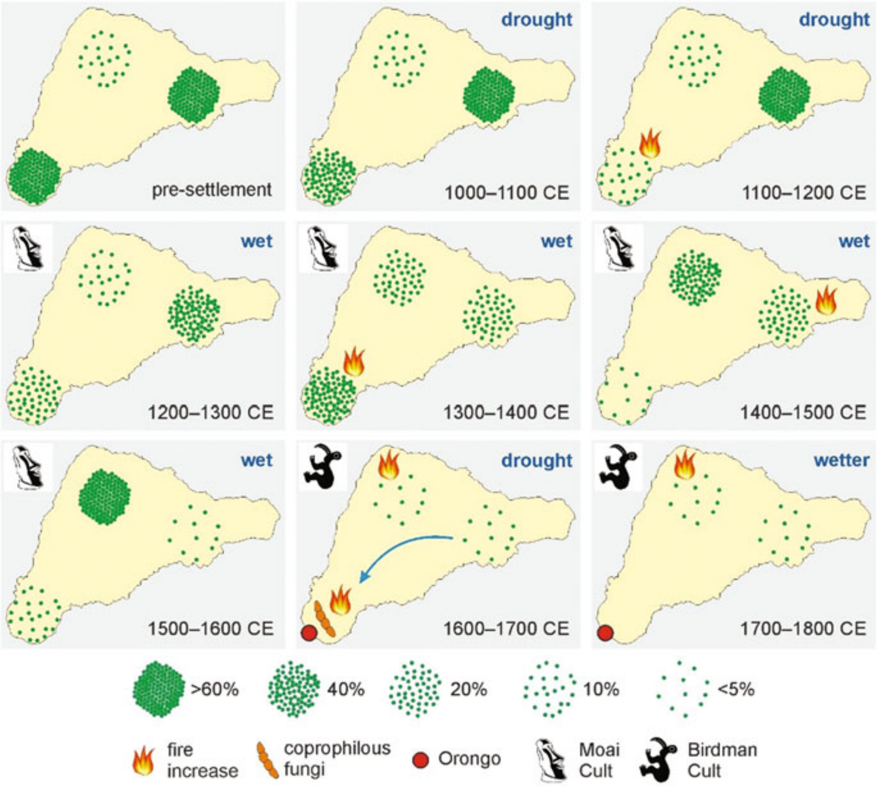

Fig. 12.9 Spatiotemporal deforestation patterns of the Rano Aroi, Rano Kao, and Rano Raraku areas and their potential drivers after Polynesian settlement. Forest cover was estimated from the palm pollen percentage. The blue arrow indicates the relocation of the cultural core of Rapanui society from Rano Raraku to Rano Kao. Redrawn and modified from Rull (2020a)

forest responses to a sustained fire incidence. At the same time, the Rano Kao forests were recovering, likely due to favorable climates and the absence of human pressure (Seco et al. 2019). This forest regeneration was interrupted by another deforestation event (1350 CE), likely anthropogenic in nature (Seco et al. 2019).

Rano Aroi continued to be devoid of humans, and the significant forest expansion recorded between approximately 1300 and 1500 CE was likely due to the occurrence of wetter climates (Rull et al. 2015). The Rano Raraku forests disappeared after a final deforestation event by 1450 CE, coinciding with significant fire exacerbation, supporting anthropogenic causes (Cañellas-Boltà et al. 2013). At the same time, human pressure declined in Rano Kao, and its forests experienced a new regeneration trend, although this was less intense than the previous regeneration (Seco et al. 2019). At the same time, Rano Aroi was truly forested for the first time, and its forests became the densest and most extensive on the island. This forest densification could likely have been due to wetter climates and the absence of human activities in Rano Aroi. However, the situation changed by 1570 CE, when a sudden deforestation event completely removed these forests (Rull et al. 2015). This coincided with intense fire exacerbation, suggesting anthropogenic causes; however, the LIA drought would have acted synergistically by favoring forest flammability and preventing regeneration. The last deforestation event on the island irreversibly removed the Rano Kao forests by 1600 CE, coinciding with the highest human occupation of this crater (Seco et al. 2019).

Taken globally, the intensification of deforestation between approximately 1200 CE and the total disappearance of forests by approximately 1600 CE coincide with the phase of increased forest clearing formerly proposed by Mann et al. (2003) and Mieth and Bork (2015), after a phase of low-intensity ecological impact. However, the detailed reconstruction described here, based on continuous sedimentary records from the three basins suitable for paleoecological study, significantly increases the spatiotemporal resolution and provides much more detail about the patterns, processes, and possible causes of the different forest removal and regeneration events. Further efforts should emphasize the study of proxies for human presence such as coprophilous fungi and specific molecular biomarkers of human presence. The use of paleoclimatic biomarkers and an increase in the temporal resolution are also recommended.

5.4 Cultural Responses to Climatic Droughts

During the MCA and LIA droughts, Rano Raraku was totally dry, and freshwater availability was critical for human life. Polynesians arrived on the island during the MCA drought, when Lake Raraku was devoid of water, but its surroundings were still forested (Fig. 12.9). At that time, the only permanent freshwater sources were Lake Kao and the Aroi swamp. Not surprisingly, the Rano Kao forests were the first to be disturbed (Seco et al. 2019). The LIA drought and the second drying out of Rano Raraku occurred when Rano Raraku was already deforested (Cañellas-Boltà et al. 2013). The situation was more critical than that during the MCA drought, as the Rapanui population was more numerous, and Rano Raraku—the site of the *moai* quarry and a central point for the Rapanui culture by that time—was likely transformed into a badland devoid of freshwater and forests (Rull 2020a, b). Again, the only permanent freshwater bodies were Lake Kao and the Aroi swamp, which began to be fully exploited and were totally deforested by 1600 CE (Rull et al. 2015; Seco et al. 2019). Human pressure significantly intensified in Rano Kao, as manifested by the dramatic increase in paleoecological indicators of human presence and agricultural activity along the lakeshores immediately below the ceremonial village of Orongo (Horrocks et al. 2012b, 2013; Seco et al. 2019). This possibly favored the emergence of the Birdman Cult and the shift of the Rapanui cultural center from Rano Raraku to Rano Kao (Fig. 12.9).

The causes of the shift from the ancestor worship to the Birdman Cult remain controversial, but some potential explanations may be suggested from the above observations. One is the search for freshwater (Rull 2020c). Another is that the Rano Kao rocks were not suitable for *moai* carving. Indeed, the Kao crater is composed of hard basalt and was one of the quarries from which the tools to carve the softer Raraku tuff were obtained (Gioncada et al. 2010). Only 13 of the ca. 1000 known *moai* are made of basalt (Van Tilburg 1994). Robinson and Stevenson (2017) suggested that the shift from the *Moai* Cult to the Birdman Cult corresponded to a territorial restructuring in response to soil nutrient depletion in interior lands, probably due to deforestation and a long period of dryness, which is in agreement with the above paleoecological observations. It has also been proposed that the shift to the Birdman Cult corresponded to a change from a rigid, hierarchical, and dynasty-based society, which flourished during the phase of relatively stable wet climates, to a more dynamic sociopolitical organization, which represented a strategy that was better adapted to changing environmental conditions (Rull 2016a).

An additional freshwater source for the prehistoric Rapanui has been proposed, involving coastal seeps fed by the groundwater system (Brosnan et al. 2018). To obtain water from these seeps, the ancient Rapanui used to excavate pits parallel to the shoreline, known as *puna*, which are still preserved at several sites near prehistoric habitation sites. All waters found in these coastal seeps today are brackish, which led Brosnan et al. (2018) to suggest that the Rapanui drank brackish water. As rain is the only freshwater source for recharging the groundwater system, its supply should have been drastically reduced during the LIA drought, which suggests that the salinity of coastal seeps could have been higher than it is today. Therefore, it is unlikely that coastal seeps would have been major freshwater sources for circumventing the LIA freshwater crisis, which lasted for a century and a half, representing approximately six human generations (Rull 2021c).

5.5 Toward an Integrated View

The prehistory of Easter Island is a complex subject that cannot be properly understood using simplifications that favor either one or another deterministic theory. Rather, natural and anthropogenic drivers of ecological and cultural change, along with their potential feedback and synergy, should be considered to obtain a more objective explanation of the available evidence. Ideally, such a synthesis should be conducted by interdisciplinary teams including open-minded researchers from a range of disciplines. Each of these disciplines provides part of the same puzzle, and we should learn how to assemble these parts together instead of claiming to know the absolute truth using only our own particular, always incomplete, set of pieces. Here, the available paleoclimatic and paleoecological findings from the last millennia are placed in a cultural chronological framework following the archaeological, ethnographic, and historical knowledge summarized in Sect. 2 to pave the way for a more integrated view (Fig. 12.10). This should be considered as an attempt to show the potential contribution of paleoecology to an integrated view of Easter Island's prehistory. The new information and the varied approaches

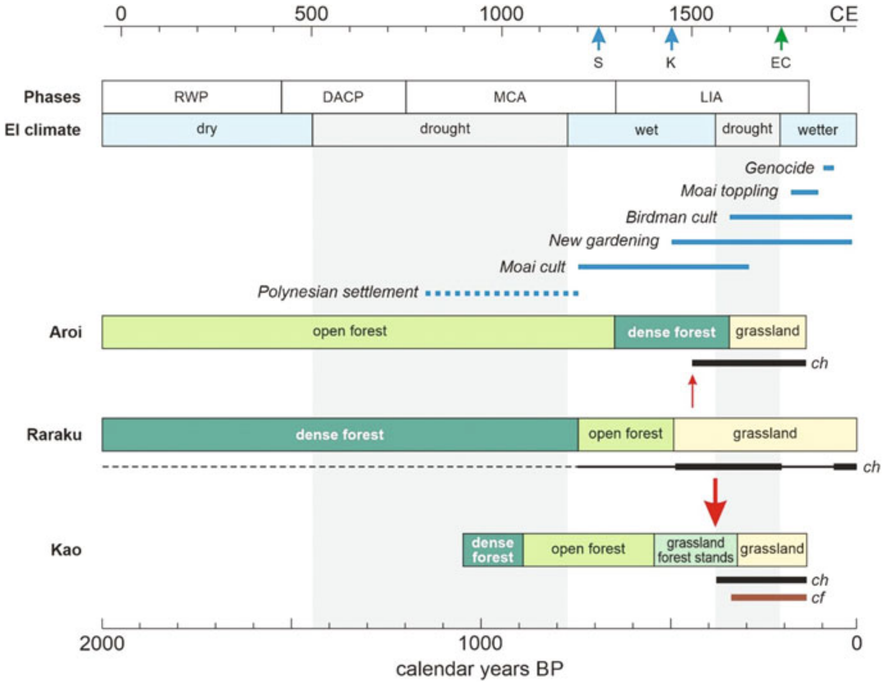

Fig. 12.10 Paleoclimatic and paleoecological scenarios of Easter Island during the last two millennia, indicating the main cultural features discussed in this paper. Drought phases are highlighted by gray bands. Blue lines represent the main cultural features, and the bars below indicate the vegetation shifts of each paleoecological site (Aroi, Raraku, Kao). Black bars represent charcoal (ch) occurrence, and the brown bar in Kao represents the presence of coprophilous fungi (cf), especially *Sporormiella*. Red arrows indicate possible geographical displacements of the Rapanui population. The green arrow indicates European contact (EC), and the blue arrows indicate the Samalas (S) and Kuwae (K) volcanic eruptions. *DACP* Dark Ages Cold Period, *LIA* Little Ice Age, *MCA* Medieval Climate Anomaly, *RWP* Roman Warm Period, *EI* Easter Island

and views arising from a wide range of disciplines compiled in this book will provide the basis for improving the preliminary synthesis presented here. The EHLFS (Environmental-Human-Landscape Feedbacks and Synergies) framework (Rull 2018), together with the multiple working hypotheses approach (Chamberlin 1965) and the strong inference method of hypothesis testing (Platt 1964), may provide a suitable methodological framework to accommodate multidisciplinary knowledge into a coherent holistic perspective. The first steps in the application of this methodology to the case of Easter Island have already been made (Rull 2018, 2020a), but there is still much room for improvement. Another possibility for addressing the problem could be the human ecodynamics (HE) approach (Fitzhugh et al. 2019), but this topic will be discussed in more depth in the final chapter of the book dedicated specifically to the integration multidisciplinary evidence on Easter Island.

Acknowledgments No funding was received for developing and writing this chapter. The author's research on Easter Island was funded by the Spanish Ministry of Education and Science, project GEOBILA (CGL2007-60932/BTE and the Catalan Agency for the Management of University and Research Grants (AGAUR), project GREB (2017-SGR415). Discussions with members of the GEOBILA project are gratefully acknowledged, especially with Núria Cañellas-Boltà, Santiago Giralt, Olga Margalef, Sergi Pla-Rabes, and Alberto Sáez. Other authors and coauthors of papers on Easter Island's paleoecology are also acknowledged, especially Roberto Bao, Hilary Birks, John Birks, Maarten Blaauw, Raymond Bradley, William D'Andrea, Encarni Montoya, Matthew Prebble, Irantzu Seco, and Blas Valero-Garcés. However, the views expressed herein are the sole responsibility of the author. Critical revisions by Núria Cañellas-Boltà, Patrick Nunn, and Christopher Stevenson contributed to improve the original manuscript.

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Chapter 13
Geological and Climatic Features, Processes and Interplay Determining the Human Occupation and Habitation of Easter Island

Alberto Sáez, Olga Margalef, Laura Becerril, Christian Herrera, James Goff, Sergi Pla-Rabes, Luis E. Lara, and Santiago Giralt

1 Introduction

Research on Easter Island's (or Rapa Nui's) prehistory has mainly been approached from archeological and paleoecological perspectives. The reconstruction of changes in island society has been based largely on the evidence of anthropic activities found in archeological sites and on paleoenvironmental reconstructions. These

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_13

reconstructions characterized the evolution of the island's lakes and the changes in vegetation. Many studies address the date of the first human arrival and the origin of those colonizers, two issues that are still controversial. Another recurring theme has been the scientific effort to reconstruct the deforestation of the landscape focusing on the drastic deforestation during fourteenth fifteenth centuries. There are two groups of authors on this topic: those arguing that changes in Easter Island society and landscape were mainly the result of anthropogenic factors (Flenley and King 1984; Mieth and Bork 2005; Hunt and Lipo 2006; Wilmshurst et al. 2011; Stevenson et al. 2015, among others), and those that propose dynamic models combining both climate change and social drivers (Nunn 2007; Lima et al. 2020; Rull 2021).

Within this scientific framework the surface geology of Easter Island has tended to be investigated through specialized studies that have described isolated geological processes that have taken place over different time scales (e.g., González-Ferrán et al. 2004; Mieth and Bork 2005; Herrera and Custodio 2008; Sáez et al. 2009; Cortez et al. 2009). These works have rarely analyzed the causal relationships between different geological processes themselves, and their interactions with recent and past climate changes. Consequently, this has resulted in a biased and limited analysis of the complex role played by these geological processes and their real and potential influence on the human occupation and societal development of Easter Island.

This work gathers together information concerning the most significant Easter Island geological and climatic processes that may have influenced human occupation and the social interaction of its inhabitants during the last millennium. In Sect. 3 of this work, we review the available knowledge about the geological processes that controlled the island formation, the main geomorphological features, and the distribution of rock units in order to understand the origin of the island's relief, hydrology, soil formation, and the inventory of building materials and lithic tools. In Sect. 4, we discuss the main soils of the island with respect to their fertility, preferred crop types, gardening, pigment production, and the erosive processes affecting some parts of the island. In Sect. 5, we introduce the climate and vegetation changes that occurred over the last millennium using stratigraphical analysis of wetland sedimentary sequences with a particular focus on the arrival of first colonizers and the process of the island's deforestation. In Sect. 6, we propose a new hydrogeological model for the island including a discussion of the influence

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of past droughts and deforestation on the main aquifer of the inland. In Sect. 7, we introduce rapid, high-energy, geological phenomena such as tsunamis. Recent and historical data indicate that these mainly impacted the coastal constructions of Easter Island in prehistory. Finally, in our conclusions we discuss the interaction between all geological processes and their destructive or constructive influence on Easter Island's ancient societies.

2 Present and Past Climate in Easter Island and in the SE Pacific Region

At present, precipitation on Easter Island changes linearly with elevation. Thus, the lowlands receive between 1150 and 1300 mm/year of rain, whereas the highlands receive up to 2200 mm/year (Puleston et al. 2017). Potential evapotranspiration is about 850–950 mm/year (Pincheira 2003). A seasonal pattern can be recognized with the wettest month being May (around 153 mm) and the driest, October (68 mm) (data from the airport weather station). Air temperature at the lowland airport weather station varies from 20.2 °C in February to 15.4 °C in August. Rainfall data from 1950 CE to 2020 CE indicates a significant interannual variability in precipitation, which seems not be related to the El Niño-Southern Oscillation (ENSO) (MacIntyre 2001; Genz and Hunt 2003).

During the Late Pleistocene-Holocene period, the climate of Easter Island and the SE Pacific region was subjected to global changes in temperature and precipitation resulting from the orbitally driven periods of the Last Glaciation, Interglacial transition, and Holocene interglacial (Fig. 13.1). These periods have been recognized from the numerous climate reconstructions carried out within the circum-Pacific region and have also been well recorded in the Rano Raraku lake facies sequence and its pollen associations (Azizi and Flenley 2008; Sáez et al. 2009; Cañellas-Boltà et al. 2013, 2016). Since 12.5 cal ka BP, the onset of the Holocene in Easter Island was characterized by a significant drop in lake water level that transformed the bottom of the Rano Raraku crater in a mire with active peat accumulation. During the Early Holocene, these drier conditions led to a decrease in palm forest pollen and an increase in littoral vegetation including sedges and ferns and the presence of *Dianella*, the main herb (flax lily) found in the pastures of the island (Cañellas-Boltà et al. 2016). During the mid-Holocene, some episodes of wetter conditions occurred around 7–5.6, 5.5–4.3 ka BP, and these are marked by an increase in palm pollen, a decline in *Dianella,* and the presence of *Cyperaceae* in the littoral wetland environment. From 2.4 ka BP, the record indicates the final decline of palm pollen juxtaposed by the expansion of grasses including the presence of *Verbena litoralis*, a ruderal weed commonly associated with human-disturbed sites, and the increase of charcoal, all suggesting an initial human presence on Easter Island (Cañellas-Boltà et al. 2013, 2016). This early human presence was probably scarce and not continuous in time as it did not leave any archeological record to date.

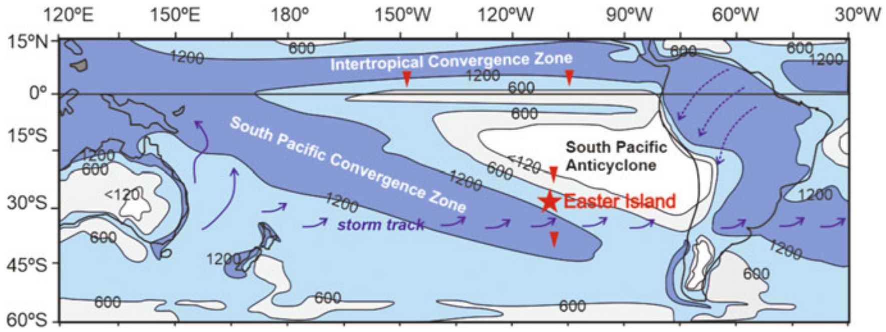

Fig. 13.1 South Pacific rainfall rate map (mm/year) showing the main atmospheric systems. Note that because of its location, Easter Island was in drought conditions when the ITCZ shifted latitudinally to the south (red arrows) during the MCA and LIA periods (modified from Sáez et al. 2009)

During the last millennium, centennial timescale hydrological changes have occurred in the SE Pacific region that have resulted from significant and frequent changes in the ocean-atmosphere circulation in the tropical Pacific region. ENSO was key to control these episodes of latitudinal shifts of the Intertropical Convergence Zone (ITCZ) (Moy et al. 2002; Yan et al. 2015). These shifts led in turn to the migration of the South Pacific Anticyclone (SPA) causing westerly storm tracks to pass to the south of Easter Island and forcing dry conditions (Sáez et al. 2009) (Fig. 13.1).

During the Medieval Climate Anomaly (MCA, ~930–1170 CE) a significant southern migration of the ITCZ (Higley et al. 2018) during a relatively low frequency of ENSO events (Conroy et al. 2008; Sachs et al. 2009) induced a dry period on Easter Island and in the Patagonian mid-latitudes (Sáez et al. 2009). Circa 1300 CE, between the MCA and Little Ice Age (LIA, 1400–1850 CE) periods, temperature decreased which together with an increase in ENSO frequency caused wetter conditions in most of the Pacific Basin (Nunn 2007). During the LIA a new southward ITCZ shift occurred, and the ENSO frequency decreased generating a new dry period on Easter Island. Finally, during the Industrial Era (IE; 1850 CE to Present) wetter conditions were established because the ENSO frequency increased again and the SPA-ITCZ tended to shift to more northerly latitudes.

Notably, these climate changes altered large-scale rainfall patterns on Easter Island and greatly influenced deforestation phases, but they also controlled the timing of human colonization of Eastern Polynesian islands by the modulation of the dominant winds (Nunn 2000, 2007; Sear et al. 2020).

3 The Volcanic Origin of the Easter Island

3.1 Formation and Age

Easter Island represents the emerged section (507 m a.s.l) of a colossal volcanic complex whose base is located at ca. 2800 m depth, creating a total height of around 3300 m (Fig. 13.2a). This island is part of the Easter Seamount Chain (ESC) located offshore from the Peru-Chile Trench on the Nazca Plate (Fig. 13.2b). The island covers an area of 166 km^2, with an estimated subaerial volume of ca. 23.5 km^3 that represents only 7.8 % of the entire volcanic edifice, which has a total volume of almost 300 km^3 according to GEBCO bathymetry (15 arc-second grid $\approx$ 450 m resolution; GEBCO 2020). Despite pioneer efforts by Baker et al. (1974), Clark (1975), Clark and Dymond (1977), O'Connor et al. (1995), and Miki et al. (1998), there is still a lack of robust geochronology for Easter Island, fueled largely by a controversy concerning the location of the hotspot (Ray et al. 2012). Published ages for Easter Island are as old as 2.5 Ma (Clark and Dymond 1977) with seamounts to the west spanning the last 3 Ma (O'Connnor 1995). Unpublished ^{40}Ar/^{39}Ar geochronology suggests a younger age for the subaerial stage in accordance with paleomagnetic data for the emergence at ca. 0.8 Ma (Isaacson and Heinrichs 1976; Miki et al. 1998; Brown 2002) and Late Pleistocene ages obtained for some of the most recent lava flows (ca. 0.1 Ma, Clark 1975).

The island consists of three major overlapping volcanoes: Poike, Rano Kao and Terevaka (Fig. 13.2c). These three volcanoes would have experienced a similar evolution characterized by the construction of a basaltic shield edifice with a summit caldera, and subsequently, flank fissure activity with eruption of more evolved magmas (González Ferrán et al. 2004; Vezzoli and Acocella 2009). Poike and Rano Kao are the largely eroded oldest volcanoes of the island, formed by a succession of lavas intercalated with pyroclastic material. They have also experienced associated phreatomagmatic explosive phases (González-Ferrán et al. 2004). Both present a late construction phase with the extrusion of high SiO_2 domes. Terevaka is the most recent shield volcano with a number of Holocene flank vents and with a succession of basaltic lavas emitted from fissure vents aligned NNE-SSW, NE-SW, and WNE-ESE (González-Ferrán et al. 2004; Vezzoli and Acocella 2009). Perimetral vents near the present shoreline have emitted basaltic lavas representing the most recent eruptive products of this complex (Fig. 13.2c).

In spite of having emerged almost 1 My ago, the island was only occupied about $\approx$1200 years ago, most probably because of its isolation in the Pacific Ocean. The geological evolution of Easter Island provides a first-order control for a number of natural processes. Surface morphology conditions, local climate, water storage and, as already pointed by Simpson Jr. (2014), island's volcanoes, ultimately gave the raw materials necessary to support human settlement. Therefore, volcanism is responsible for the birth and growth of the island's volcanoes conditioning not only its topography and bathymetry, but also the paleoecology and biological processes as well as the ocean dynamics around this island, and the pattern of settlements.

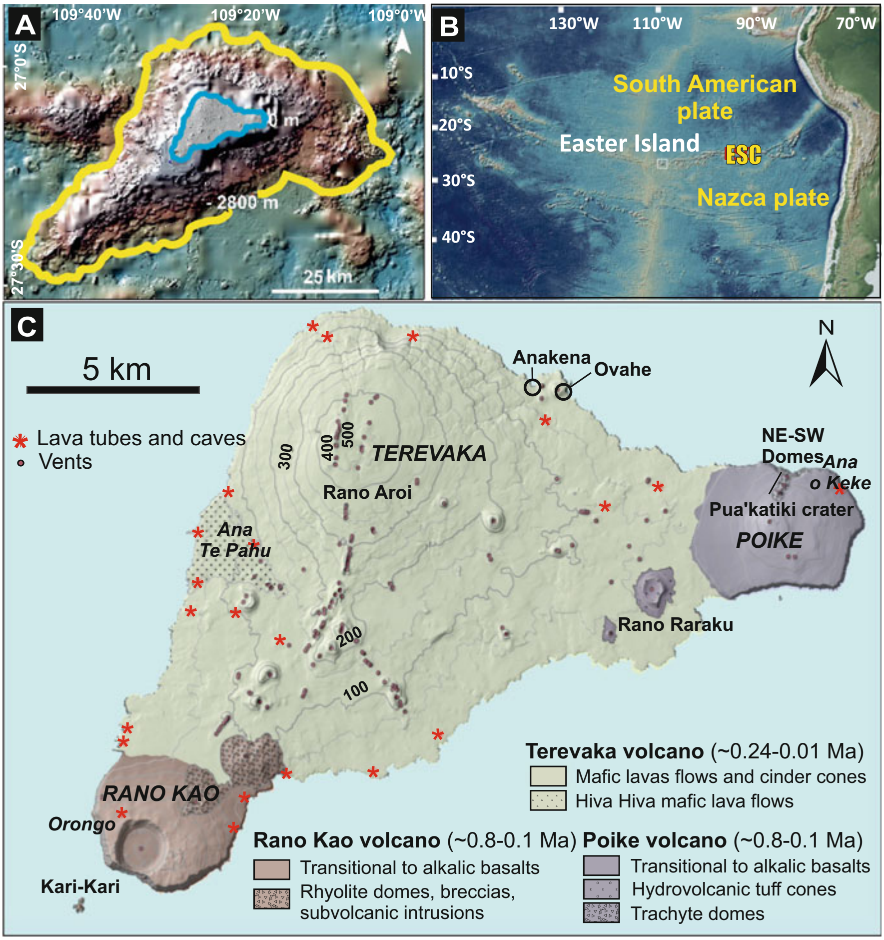

Fig. 13.2 (**a**) Easter Island volcano edifice. Ocean bottom is at 2800 m b.s.l (yellow line); Island base is at 0 m. a.s.l (blue line). Bathymetry from GeoMapApp (www.geomapapp.org). (**b**) Location of Easter Island along the Easter Seamount Chain (ESC). (**c**) Simplified geological map of Eastern Island. Rano Kao and Poike (~0.8–0.1 Ma), and Terevaka (~0.24–0.01 Ma) volcanoes are shown

3.2 The Geomorphological Evolution of the Island

The geomorphological evolution of volcanic islands in general, and of Easter Island in particular, from their start as a seamount to the island emergence, results from a delicate balance between magmatism (extrusion/intrusion rates), tectonics (subsidence/uplift and strain rates), and erosion (mass wasting, sedimentation, and subaerial/marine erosion) (Ramalho 2011). Current landforms on the island have resulted from the interplay between these constructive and destructive forces. These landforms determined the areas to be occupied by the first inhabitants.

Easter Island can be considered an active volcano, with recent activity focused on Terevaka and peripheral vents (Lara et al. 2020). Radiocarbon dated paleosols underneath basal lavas from Terevaka indicate that the last volcanic eruptions occurred between 11 and 6 kyr (Lara et al. 2018) with no evidence for eruptive activity coeval with human settlement. The building of the Terevaka volcano saw it joint as a composite with two ancestral volcanoes and become extensively eroded by the sea. However, inland erosion is less and primary constructional landforms are still well preserved.

The remnant Poike volcano is almost 5 km wide and covers 15.8 km^2, with a maximum height of 370 m a.s.l. (Pua' katiki crater). It has active sea cliffs on the north, south, and east flanks and it presents a characteristic ochre-orange colored paleosol exposed as a consequence of surface erosion. The youngest part of the Poike volcano consists of three small trachytic lava domes (220 m wide, 40–55 m high), aligned along a NE-SW trending eruptive fissure (Fig. 13.2c).

Rano Kao volcano is characterized by a caldera with a crater 1.5 km wide, inside of which Lake Kao, 1.1 km in diameter and 200 m below the rim, is found. The remnant volcano covers 14.5 km^2 with a maximum height of 324 m a.s.l. The south flank of the volcano (Kari-Kari) is marked by a steep sea cliff, the basal erosion of which is causing a rapid collapse (Quezada et al. 2009).

Terevaka volcano is the highest elevation on the island (507 m a.s.l) and it represents about 82% of the island surface ($\approx$136 km^2) giving the current shape to the present volcanic complex. It is characterized by gentle slopes dotted by monogenetic centers. Despite being the youngest volcano, Terevaka has active cliffs (10–120 m high) along the northern and western coasts. Erosion also produces constructive landforms in the island represented by low angle plains.

The volcanic nature of the island has mostly generated rocky coasts. Despite this, there are two small sandy beaches on the north coast of the island (Anakena and Ovahe) occupying small depressions along the coastline (Fig. 13.2c). These beaches were created during the Holocene sea level highstand from the accumulation of sand grains composed of the fragments of marine calcareous organisms and coral reef (Glynn et al. 2003) produced on a narrow platform. Anakena beach is in a deep inlet which provided shelter for the first inhabitants (Hunt and Lipo 2006).

3.3 Volcanic Eruptions and Their Rocks as a Resource for Settlers

Eruptive activity on Easter Island has been dominantly effusive with frequent generation of mafic lava fields mostly related to the Terevaka volcano, although more evolved compositions are also present (Baker et al. 1974) (Fig. 13.2c). Moreover, there are several monogenetic volcanoes that include cinder, spatter, tuff cones, and domes, all of them associated with mild explosive activity, with eruptive products ranging from tholeiitic basalts to olivine alkaline rocks (Baker et al. 1974; Haase et al. 1997) (Fig. 13.2c).

The jointing and cracking of these lavas coupled with their high porosity provided excellent geological conditions for the development of groundwater reservoirs. There is also evidence to suggest that some lava tube/caves were managed in a way that captured surficial water thus playing a significant role in groundwater recharge (Kiernan et al. 2003) (See Sect. 6 for more information).

Lava flows from Terevaka volcano cover a significant area with the most recent *pahoehoe* flows reaching the ocean. Lava tubes formed by these *pahoehoe* flows ultimately formed caves, locally called *ana*, many of which were once used as dwellings by the Polynesians. While the total number of these caves is unknown, the largest and best example of a lava tube on the island (more than 7 km long) is Ana Te Pahu (Drum cave), which is associated with the Maunga Hiva Hiva eruption, one of the most recent eruptive events (Fischer and Love 1993; Haase et al. 1997; O'Connor et al. 1995). This tube was used by locals not only as a living space, refuge, and water reservoir, but also for gardening because of the humid conditions. While many of the island's lava tubes were used as dwellings they also served as both ritual and burial sites (Smith 1961) (Fig. 13.2c). Another well-known lava tube is Ana o Keke (Cave of the White Virgins; Cave of the Sun's Inclination) that lies on northeastern edge Poike. This lava tube was primarily used for ritual purposes in which young girls were confined in the darkness to bleach their skin to match the fairness of the gods.

Lavas from the island have different features with a group sharing some similar physical properties such as density ≤ 2.00 g/cm^3 and high total porosity that make them both light in weight and easy to shape into tools (Gioncada et al. 2010). Accordingly, these rocks had many different uses depending on their composition and physical properties. They were extensively used in the construction of *ahu*, where large blocks were assembled to support *moai*. *Ahu* were constructed of huge, flat mafic rocks representing the most resistant material that could be easily found along the coastline. Lava rocks also served in the construction of stone houses of Orongo. Basaltic lavas also provided the medium for the rock art creations of petroglyphs and pictographs while obsidian was particularly chosen for tools and sharpeners (Simpson Jr. 2014 and references therein). Indeed, the obsidian found at Maunga Orito is generally a clear, greenish brown glass with conchoidal fracturing, and the remains of stone tools produced from this material are still found scattered across the island.

In contrast to effusive eruptions, volcanic activity in the form of phreatic or Surtseyan hydromagmatic explosions also occurred. These events formed tuff cones, some of them creating craters that today act as freshwater reservoirs (lakes or mires) such as those of Rano Kao, Rano Aroi, and Rano Raraku. The Rano Raraku volcano was formed more than 0.21 My ago by the interaction of shallow seawater with magma (Vezzoli and Acocella 2009), producing soft, yellowish, tuff rocks forming horizontal beds that became ideal for the production of ~96% of the *moai* sculptures in its famous quarry (van Tilburg et al. 1994). Basaltic xenoliths are often found inside these tuffs and were used as lithic tools for carving (Kiernan 1982).

In addition, pyroclastic rocks related to explosive eruptions from cinder and spatter cones are found around Terevaka volcano. These materials served as the *moai* top-knots (Baker 1993), blackish when fresh but bright red after weathering (Kiernan 1982).

Soils are the other important product of volcanism. The volcanic soils of the island were formed during periods between major eruptions, by weathering of fresh volcanic material, mostly ash and to a lesser extent breccia layers from lavas. An extended explanation of island's soil, characteristics, and development is given in Sect. 4. Soils and paleosols developed iron oxides, producing reddish-orangish colors that were used also as pigments (see Sect. 4.4).

4 Soils and Agriculture

4.1 Easter Island Soil Types

The volcanic origin and derived mafic rocks determine the nature and properties of Easter Island soils. This becomes a crucial geological feature that conditioned human occupation with the combination of soil development, water availability, and topography directly related to the potential uses of the soils in terms of cultivation but also to associated risks, such as surface erodibility. Our work suggests that the chemical, mineralogical, and textural characteristics of soils found today on Easter Island (described in more detail below) can be compared to those soils present in the island during prehistoric times and which the inhabitants used for their crops.

The island is mainly dominated by andosols, except for the easternmost region (Poike area) where ferralsols have also been described (Horrocks and Wozniak 2008). Andosols are soils typically generated from volcanic ash and lava rocks (IUSS Working Group WRB 2015) and are usually young and immature, formed by the rapid weathering of volcanic material to produce amorphous or poorly crystallized silicate minerals such as allophane or imogolite, clays and oxy-hydroxides (Brady and Weil 2008). The accumulation of organic matter can be rapid due to its protection in aluminum–humus complexes, but the same process can also lead to phosphorus limitation due to its retention by adsorption on highly reactive mineral surfaces. The water retention capacity of andosols can be quite high, but it is strongly dependent on its relative proportions of porosity, texture, and stoniness. Ferrosols on Easter Island are only found in Poike area. Poike, together with Rano Kao, was the first emerged volcanoes of the island, constituted by lava flows ca. 1 Ma old (Vezzoli and Acocella 2009). Ferralsols are derived from long and deep weathering processes and they are dominated by a fine sized fraction composed of clays with low cation exchange capacity (up to 60% of kaolinite) and a high oxide and hydroxide content that gives them their characteristic reddish or yellowish color (Horrocks and Wozniak 2008; IUSS Working Group WRB 2015).

4.2 *Edaphic Features, Soil Texture, Nutrients, and Composition*

In general, Easter Island soils are very stony and are in general quite shallow, mainly with depths less than 45 cm (Fig. 13.3a, b) (Honorato and Cruz 1999). Soil depth is mainly constrained by the age of the bedrock, but it also conditioned by topography as deeper soils are found on flat areas and gentle slopes, like the lowermost parts of the volcanic cones (Alcayaga and Narbona 1969). Therefore, soil depth across the island is highly variable and is represented by a stepped micro relief (Honorato and Cruz 1999).

Detailed information on edaphic parameters from the soils of the island has been provided by several reports oriented towards soil management or erosion prevention (Alcayaga and Narbona 1969; CIREN 2013). An average of different parameters from 12 soil series published on CIREN (2013) is presented below (Table 13.1). Easter Island soils are moderately acidic (pH between 5.03 and 6.13) and dominated by clay and silt fractions. Soils from the Poike region have lower pH values (pH ≈ 5) and higher clay percentages (>45%) along with those described in the Kao series (>50%). Halloysite is the dominant clay, associated with variable amounts of allophane on surface samples while on deeper samples, this clay appears combined

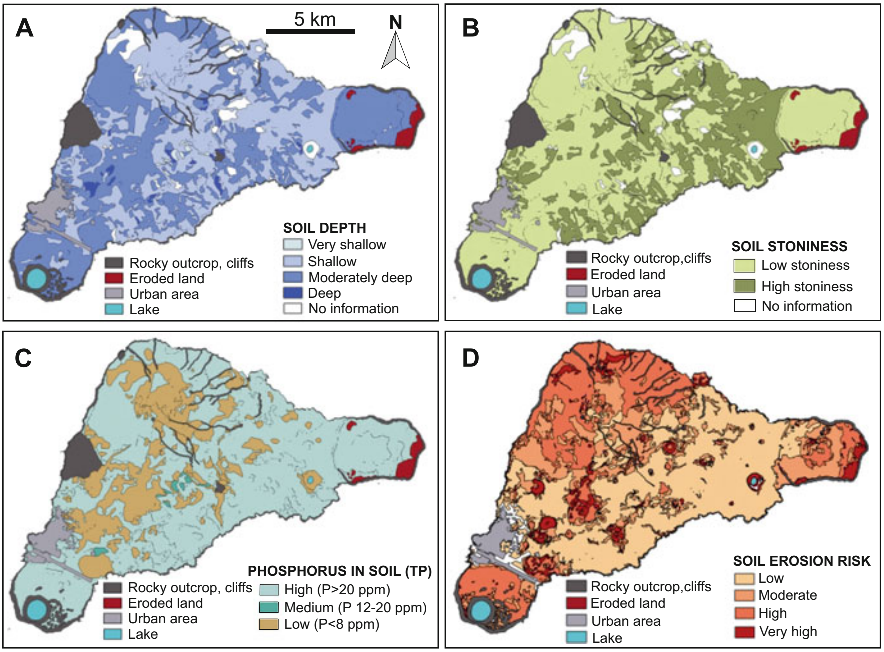

Fig. 13.3 (**a**) Easter Island map showing distribution of soil depth. (**b**) Stoniness degree in soils. (**c**) Phosphorus content in soils. (**D**) Erosion risk of soils. Data from CIREN (2013)

Table 13.1 Average values and standard deviation (SD) of several edaphic parameter from 12 soil series published in CIREN (2013). Soil samples were retrieved from the first 15 cm. Between 3 and 6 samples were taken of each series originally defined in Alcayaga and Narbona (1969). The location of each series is represented on map of Fig. 13.4. Soil parameters: *CE* electrical conductivity, *TN* total nitrogen, *TP* total phosphorus, *TK* total potassium, *CIC* cation exchange capacity

Series	Soil parameters							Exchangeable cations				Texture					
	pH	CE	TN	TP	TK	Organic matter	CIC	Ca	Mg	K	Na	Sand	Silt	Clay	Bulk density	Field capacity	Permanent wilting point
		dS/m	mg/kg	mg/kg	mg/kg	%	meq/ 100 g	meq/ 100 g	meq/ 100 g	meq/ 100 g	meq/ 100 g	%	%	%	g/cc	%	
1. Orite (n = 3)	5.83	0.28	35.33	15.33	194.00	4.77	34.40	6.37	5.03	0.50	0.47	22.33	35.67	42.00	1.07	34.97	23.70
SD	0.17	0.06	2.87	6.55	44.09	0.49	2.02	0.54	0.47	0.11	0.08	0.94	3.77	4.32	0.01	3.00	0.75
2. Rano Aroi (n = 3)	5.33	0.20	36.67	8.00	22.67	15.10	48.23	0.39	0.35	0.06	0.12	47.33	27.33	25.33	0.84	46.73	35.37
SD	0.12	0.12	3.77	2.16	9.29	4.64	6.58	0.02	0.17	0.02	0.07	0.94	1.89	0.94	0.16	4.86	4.21
3. Hanga Te Tenga (n = 3)	6.13	0.38	31.33	177.33	558.33	4.57	30.20	7.17	6.60	1.41	0.73	21.67	37.00	41.33	1.06	35.40	23.63
SD	0.33	0.12	13.91	137.85	196.26	0.66	1.68	4.08	1.39	0.49	0.17	3.68	1.41	2.49	0.06	5.87	1.93
4. Vaitea (n = 6)	5.65	0.23	40.50	45.33	51.17	10.53	44.70	3.75	2.06	0.13	0.15	35.83	33.50	30.67	0.85	48.62	32.12
SD	0.24	0.08	6.55	50.38	40.73	1.08	5.27	3.64	2.10	0.10	0.08	8.25	3.82	7.09	0.04	3.48	2.15
5. Te Reva Reva (n = 3)	5.97	0.16	24.67	4.67	186.33	5.27	29.20	3.97	3.18	0.47	0.31	20.67	36.00	43.33	1.09	40.17	27.60
SD	0.19	0.05	2.49	0.47	136.09	1.33	3.63	3.44	2.98	0.35	0.12	12.04	4.32	13.30	0.08	4.00	2.43
6. Akahanga (n = 3)	5.87	0.29	36.67	44.33	375.67	4.43	27.10	4.43	4.90	0.96	0.27	22.00	30.67	47.33	1.08	33.70	24.73

(continued)

Table 13.1 (continued)

Series	Soil parameters							Exchangeable cations				Texture					
	pH	CE	TN	TP	TK	Organic matter	CIC	Ca	Mg	K	Na	Sand	Silt	Clay	Bulk density	Field capacity	Permanent wilting point
		dS/m	mg/kg	mg/kg	mg/kg	%	meq/ 100 g	meq/ 100 g	meq/ 100 g	meq/ 100 g	meq/ 100 g	%	%	%	g/cc	%	
SD	0.05	0.09	6.18	41.99	293.80	1.11	3.85	1.02	0.36	0.75	0.09	5.89	3.40	5.25	0.05	1.74	0.97
7. Naure (n = 4)	6.10	0.31	41.00	8.50	151.25	7.75	43.18	7.55	5.40	0.39	0.40	40.00	36.00	24.00	1.03	42.78	27.60
SD	0.12	0.03	15.73	3.57	51.04	1.07	6.79	3.28	1.55	0.13	0.15	4.69	2.83	3.16	0.05	1.92	1.61
8. Poike (n = 3)	5.03	0.24	32.67	45.00	74.33	4.13	33.40	0.90	1.40	0.19	0.19	26.33	24.33	49.33	0.91	37.43	26.73
SD	0.05	0.03	5.44	41.21	39.84	0.70	5.81	0.29	0.43	0.10	0.05	5.73	3.77	9.29	0.04	3.32	2.70
9. Rano Kao (n = 3)	5.77	0.19	28.33	73.00	121.67	6.30	35.53	1.77	2.84	0.31	0.36	26.00	24.67	49.33	1.04	40.27	29.23
SD	0.29	0.02	1.25	80.45	79.97	2.82	5.93	1.51	2.59	0.20	0.08	7.12	5.25	12.36	0.03	6.32	2.24
10. Orione (n = 3)	6.47	0.44	33.33	105.67	720.67	4.97	30.00	9.13	8.10	1.83	0.83	30.33	34.33	35.33	1.03	32.37	23.63
SD	0.19	0.10	12.55	54.30	235.57	1.32	0.16	2.12	0.85	0.61	0.28	3.30	0.47	3.40	0.07	1.80	0.74
11. Punapau (n = 4)	5.75	0.33	42.50	44.25	245.00	7.85	40.35	4.10	4.30	0.63	0.41	25.25	35.25	39.50	0.99	43.73	27.93
SD	0.36	0.09	11.93	5.67	128.84	2.80	5.11	2.06	2.37	0.33	0.26	11.30	4.44	14.17	0.18	12.08	3.82
12. Toa toa (n = 3)	6.07	0.31	39.67	57.33	301.67	7.47	41.70	7.73	5.30	0.77	0.47	27.33	32.00	40.67	0.95	41.43	26.93
SD	0.09	0.01	11.32	4.50	31.75	3.52	11.41	1.13	0.88	0.08	0.21	18.37	5.35	22.17	0.08	6.26	2.19
13. Eroded (n = 1)	5.00	0.69	31.00	1.00	343.00	1.30	24.60	0.97	0.96	0.88	2.30	15.00	23.00	62.00	0.82	48.50	36.80

with kaolinite, hematite, and gibbsite as well as other hydroxides (Alcayaga and Narbona 1969). The clayey texture of the soil together with the low values for base saturation is indicative of relatively rapid weathering and the lixiviation of bases lost by percolation. The water retention capacity is quite good which permits minimum conditions for cultivation in parts of the island despite the shallow depth of the soils.

The total nitrogen (TN) values of Easter Island soils are in general quite low, ranging between 24 and 40 ppm, and correlate with the percentage of organic matter ($R^2 = 0.51$). The high percentage of organic matter indicates the availability of N through mineralization despite its low concentrations. Total phosphorus (TP) concentrations are variable across the different soil series sampled probably indicating differences in substrate P concentrations or associated with different adsorption capacities (Fig. 13.3c). Average values are relatively high, especially on the Hanga Te Tenga, Orione, and Kao series (Table 13.1). However, an important portion of this phosphorus can be occluded by adsorption on clay and oxide surfaces and therefore is not easily available for plant productivity. Available P (P-Olsen) fluctuates considerably among the surface soil samples (0–15 cm) and Alcayaga and Narbona (1969) reported maximum values above 250 ppm and minimum values around 27 ppm. Soil organic matter is moderately high especially in surface samples (close to 6%) most probably due to favorable climate conditions that led to its association into aggregates or the formation of aluminum–humus complexes. Very high organic matter values (>10%) are found on Rano Aroi and other sectors in the center of the island.

The edaphic features of Rapa Nui soils are habitual in relatively young andosols under tropical or subtropical regimes (Brady and Weil 2008). Considering the combination of the described variables, about 26% of the island surface is suitable for cultivation today (land-capability classification I to IV according to the Soil Conservation Service of the U.S. Department of Agriculture) while 66% is suitable for permanent grasslands or forests but not for crops (land-capability classes from V to VII) (Fig. 13.4) (CIREN 2013; Klingebiel and Montgomery 1961).

4.3 Soil Erosion Risk

A report from CONAF (1981) suggested that 20% of the island suffered from active erosive processes at the year of publication, especially on the hillsides of the main and secondary volcanoes where the slope can be greater than 15%. On the other hand, Honorato and Cruz (1999) indicated that more than the 50% of the island's soil surface had high and very high erodibility categories. Sheet erosion, resulting in the loss of finer particles by runoff is the most generalized type of erosion on the island. Rill, laminar, and gully erosion represent the most significant types of sheet erosion leading to a total and irreversible loss of soil.

A detailed and updated characterization of soil erodibility and potential erosion on the island is presented in CIREN (2013). Soil erodibility indexes are calculated from soil texture, soil organic matter, permeability, and soil depth. In this work,

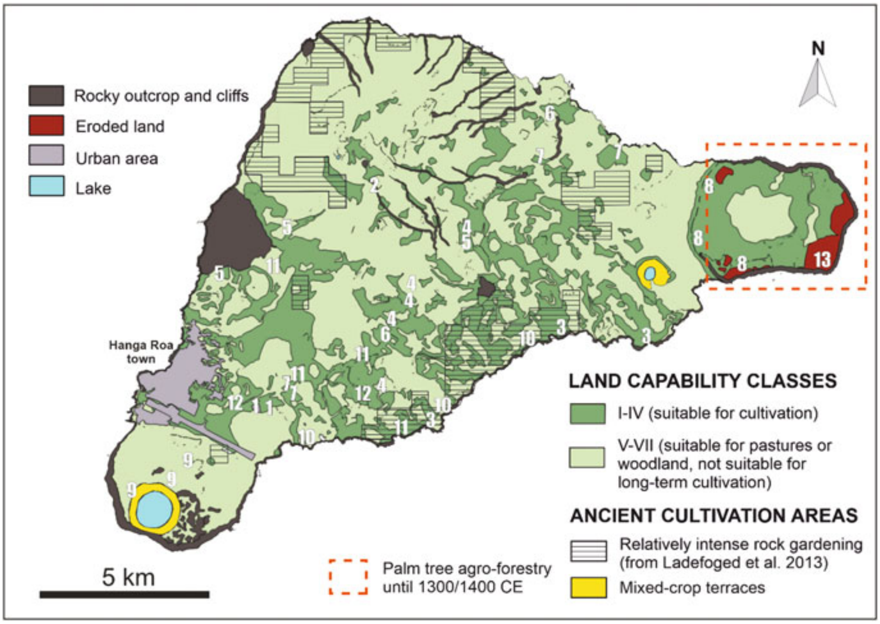

Fig. 13.4 Easter Island map showing distribution of current soil land-capability classes and prehistoric cultivation techniques as rock gardening and terraces. White numbers indicate location of soils series in Table 13.1 (point 2 indicates three nearby series of Rano Aroi)

a combination of soil erodibility and slope inclination (the physical risk) together with runoff intensity and climate conditions (topo-climatic risk) is used to obtain the potential erosion index. The resulting output does not include the effect of vegetation cover and therefore it can be used as an estimate of the potential erosion risk faced by the early inhabitants of the island under similar climate conditions (Fig. 13.3d).

As shown on Fig. 13.3d, the highest erosion risk today is concentrated in the Rano Kao and Poike areas, but also on the northern slope of Terevaka summit. The risk is also high on the margins of small volcanic cones. The different episodes of deforestation described in the island (Rull et al. 2016, 2015) probably contributed to reduce the water holding capacity of the organic matter and soil, therefore increasing erodibility and negatively impacting the potential risk of erosion. This has been studied in detail in the Poike region where Mieth and Bork (2005) demonstrated that severe erosion started after woodland clearance around 1280 CE and lasted for about 640 years. These authors suggested erosion rates ca. 8.6 Mg/ha/year during this period. The erosion rates are much higher today in the three gully systems caused by runoff in areas intensively grazed on Poike peninsula between 1930 and 1970 CE. In these gully systems erosion rates vary between 193 and 650 Mg/ha/year (Mieth and Bork 2005).

4.4 Present and Past Cultivable Soils Distribution

Besides the already explained phosphorous occlusion and the nitrogen availability, the shallowness and stoniness of Easter Island soils constitute the most important impediment for the development of agriculture.

Archeological and paleoenvironmental studies revealed that prehistoric Easter Island farmers cultivated sweet potato, taro, yam, sugar cane, and banana (Horrocks and Wozniak 2008). Temperature and precipitation are almost optimal for sweet potato cultivation but not for taro, yam, or sugar cane. This is mainly because these plants require wetter conditions and could suffer from hydric deficits during the dry season (Louwagie et al. 2006). To overcome hydric stress people developed adaptive strategies, using a lithic mulch, and concentrating crop distribution close to available fresh water. This need for hydric resources conditioned the location of human activity around the Rano Kao and Rano Raraku lakes and the Aroi swamp. For the same reason, inside the Rano Kao and Rano Raraku craters, humans developed mixed crops on terraced soils because of the ability to irrigate them using water from the lakes inside the crater (Horrocks and Wozniak 2008, Horrocks et al. 2012a, b, Sherwood et al. 2019).

Rock gardening was the primary agronomic practice of prehistoric Easter Islanders and was applied over 2.5–12.7% of the island's surface (Fig. 13.4) (Ladefoged et al. 2013). This technique consisted of intentionally (1) mixing small rocks into the subsurface soil or (2) spreading larger rocks over the ground surface (Stevenson et al. 2002). Rock gardening provided several advantages such as protection against wind, soil erosion, and temperature fluctuations. Subsurface temperature has been shown to have been on average ca. 2 °C lower on mulched sites than in adjacent non-mulched areas, reducing evapotranspiration and retaining soil moisture (Ladefoged et al. 2010, 2013). However, rock gardening was rare above 250 m.a.s.l., probably because higher elevations received greater rainfall that contributed to a higher soil moisture content and to a more effective leaching of nutrients (Ladefoged et al. 2010; Wozniak 1999).

In general, Polynesian societies adapted to variable climate conditions and soil fertility across the different Pacific islands. In the Hawaiian archipelago, large dryland agricultural systems developed on the younger islands, while on the older ones production was supported by irrigated wetland agriculture (Vitousek et al. 2004). The most remarkable agronomic practice, rock gardening, was not exclusive to Easter Island and it has been also described in New Zealand and other Polynesian islands (Barber 2010), but it was not required on islands with wetter (rainier) conditions (DiNapoli et al. 2018).

4.5 Other Soil Uses

Easter Island people also used their soils for other purpose. On the southern flanks of Terevaka and Poike hundreds of anthropogenic pits have been found, not used for planting, storage, or as cooking pits. A lid-like layer of brown dark substrate covered these pits that were filled with reddish iron oxides such as hematite and maghemite (Khamnueva-Wendt et al. 2018; Mieth et al. 2019; Out et al. 2020). Recent studies indicate that the pit function was the production of reddish pigments, and the cover of a dark brown substrate is interpreted as a human made lid that implies their use as pigment storage (Out et al. 2020). These reddish pigments were produced by heating a minerogenic iron-rich substrate by using grass as fuel. However, the iron-rich substrate was not obtained from the immediately vicinity of the pits and probably came from different localities (Out et al. 2020). The reddish pigment was used for rock painting, petroglyphs, *moai* coloration, and in burials (Mieth et al. 2019 and references therein).

The first evidence of pit use is dated to around 900–1140 CE. However, their presence was continuous from ca. 1201 to ca. 1665 CE, with the greatest abundance between 1325 and 1445 CE (Out et al. 2020). This period corresponds to that of intensive land occupation and deforestation (Rull et al. 2015, 2016) and the increase in Easter Island's population (Lima et al. 2020). The continuous presence of these pits and lithic mulching are used as evidence of the cultural continuity of Easter Island society despite drastic changes in land use and environmental conditions (Mieth et al. 2019).

5 Wetlands and Climate Changes

5.1 Wetlands and Their Paleoenvironmental Significance

As stated before, three crater wetlands can be recognized on Easter Island: lakes at Rano Kao (110 m a.s.l) and Raraku (70 m a.s.l.), and the mire of Rano Aroi (430 m a.s.l.). These three wetlands accumulated non-volcanic, terrigenous, and peaty sediments during the Late Pleistocene and Holocene. Their sediment infilling sequences constitute the best climate archives of the island, principally from the determination of the age of changes in the facies, including the duration and paleoenvironmental interpretation of their sedimentary gaps, and their changes in palynological content. Since the 1980s, these lakes and the mire have been cored with the aim of analyzing their sediments. Various groups of researchers have obtained a wide range of results that have allowed the reconstruction of vegetation and climate change on the island over the past 70,000 years. Some studies interpreted long-term, late Quaternary climate changes (Azizi and Flenley 2008; Sáez et al. 2009; Margalef et al. 2013; Rull et al. 2015; Cañellas-Boltà et al. 2016). Many other studies on the uppermost sections of the cores analyzed and interpreted the human impact on the ecological system of the island and the role of climate change over the last millennium (Flenley and King 1984; Flenley et al. 1991; Dumont et al. 1998; Mann et al. 2008; Cañellas-Boltà et al. 2013; Rull et al. 2015; Seco et al. 2019).

Easter Island wetlands by themselves were not significant geological/ geomorphological elements in influencing Easter Island society, except as reserves of freshwater usable for irrigation within the craters of Rano Raraku and Rano Kao or, over the past 200 years as water for cattle. Nevertheless, the paleoenvironmental and paleoclimate reconstructions obtained from the wetland sedimentary records have helped to resolve fundamental questions such as the date of arrival and/or occupation of humans on the island and the climatic and/or anthropic causes of its deforestation. Also, data from wetlands have served to gauge patterns of population growth and changes in the occupation patterns of different sectors of the island.

5.2 Climate Changes and Societal Changes in Polynesia and Easter Island from Wetlands Stratigraphic Record

The uppermost 20 cm of core RAR-08 in Rano Raraku lake (Sáez et al. 2009; Cañellas-Boltà et al. 2013), the 220 cm of core KAO-08-03 in The Rano Kao lake floating peat (Seco et al. 2019), and the uppermost 130 cm of core ARO-08-02 in the Rano Aroi mire (Rull et al. 2015) (Fig. 13.6) record the last 1000 years of Easter Island's paleoenvironmental history. This history relates to the final phase of a deforestation trend initiated around 2.4 ka BP (Cañellas-Boltà et al. 2016). This was not a gradual process because of the concurrence of climate changing conditions and the increasing intensity of human deforestation activities.

During the last millennium, around c. 500–1200 CE, a sedimentary gap in the Rano Raraku sequence points to a dry phase (gap 1, Fig. 13.5b). Around 1070 CE, the Rano Kao sequence records a shift from dense palm forest to an open forest landscape (Fig. 13.5c). This landscape opening phase has been interpreted as climate-driven as it occurred during the dry Medieval Climate Anomaly (MCA). This dry period has also been described in Patagonian mid-latitudes and it seems to be triggered by the southern shift of south Pacific storm tracks, related to "El Niño-like" dominant conditions in this period (Fig. 13.5e, Sáez et al. 2009). Rano Aroi mire sediments did not record this drought episode, probably due to altitude effect in precipitation in the highlands of the island. Both dry conditions and persistent westerly wind anomalies during the MCA period have been argued as causing human migration from West into East including the settlement of Hawai'i, New Zealand, Cook, Society, Marquesas, and Easter islands (Goodwin et al. 2014; Sear et al. 2020).

At 1200 CE, a cooler and wetter Pan-Pacific short episode named the "1300 event" (Nunn 2007) caused the water table at the Rano Raraku site to increase, and the former mire becomes the shallow lake that can still be seen today (Fig.

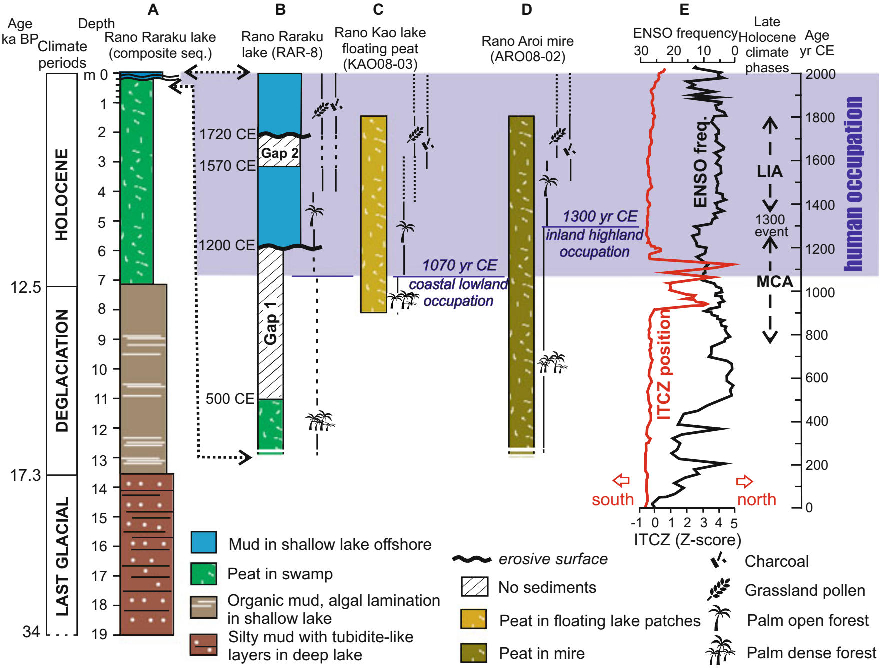

Fig. 13.5 Lithostratigraphic record and pollen contents of Easter Island wetlands with the main periods of climate change over last millennium including the date of human occupation of the lowlands. (**a**) Composite sedimentary sequence of Rano Raraku Lake; the limits of last glacial-interglacial periods match with sedimentological facies and units for the last 34 ka (Sáez et al. 2009; Cañellas-Boltà et al. 2016). (**b**) Sedimentary record of the uppermost 20 cm of core RAR-8 retrieved from Rano Raraku Lake (Cañellas-Boltà et al. 2013). (**c**) Sedimentary record of the 220 cm long core KAO08-03 retrieved from peat in the floating mat of Rano Kao Lake (Seco et al. 2019). (**d**) Upper part of the 325 cm long core ARO08-02 from peat in the Rano Aroi mire (Rull et al. 2015). (**e**) (red line) Latitudinal shifts in the Intertropical Convergence Zone (ITCZ) (Higley et al. 2018), (black line) ENSO (rainy events) frequency (Conroy et al. 2008)

13.5b). In spite of these wetter conditions, sediments of this period display palm pollen numbers lower than previous periods and signify a transition from dense to open palm forest (Fig. 13.5b). This deforestation phase has been attributed to the onset of intense human activity in the coastal lowlands of the island and activities developed Rano Raraku volcano crater that houses the *moai* quarry. Stratigraphic data from the Rano Raraku sequence constrains the human occupation of this part of the island to between 500 and 1200 CE, although the evidence of agrarian activity inside the crater is somewhat later (1320–1440 CE, Sherwood et al. 2019). Deforestation occurred in the Rano Kao peat sequence around cal. 1070 CE (Fig. 13.5c, Flenley and King 1984; Seco et al. 2019), which could be the age for the onset of intense activities in the Rano Kao sector that some centuries later would be the location of the Orongo ceremonial village. These data from Rano Kao and Rano Raraku contradict the theory of some authors who established the onset of the occupation of the island around 1200 CE based upon the artifactual evidence for human occupation found at Anakena beach (Hunt and Lipo 2006; Hunt 2007).

Around 1300 CE, a decrease in palm pollen occurred in the Rano Aroi sediment sequence, but not at Rano Raraku or Rano Kao. This latter deforestation at the higher elevations of Terevaka has been interpreted as the delayed occupation of the inner highland zone of the island with the first settlers initially occupying coastal lowlands (Rull et al. 2015; Lima et al. 2020).

Between 1420 and 1450 CE, the Raraku sediments are characterized by the dominance of Gramineae pollen and the presence of charcoal (Cañellas-Boltà et al. 2013). During the same period Gramineae pollen increased significantly in Rano Kao while palm pollen disappeared (Seco et al. 2019). Both records indicate that the final deforestation phase of island lowlands took place during this period, changing from an open palm forest towards a grassland dominant landscape with the full development of agrarian activities (Horrocks et al. 2012a, Fig. 13.5d).

Between 1570 and 1720 CE, a second sedimentary gap is recorded in Rano Raraku (gap 2, Fig. 13.5b). Within this period, the Aroi mire sediments recorded the open palm forest disappearance from the Terevaka highland zones (Fig. 13.5d), completing the total deforestation of the island and leading to the grassland dominated landscape that can be seen today. Since this last deforestation period was coeval with the global dry and cool period of the Little Ice Age (LIA) it is reasonable to attribute a double cause, climatic and anthropogenic, to the final phase of deforestation in Easter Island. Both dry conditions and the final deforestation were coeval to a demographic decline of the Easter Island population until 1760 CE (Lima et al. 2020) and it has been argued that both environmental changes were the cause of significant socio-cultural changes in Easter Island society, such as the transition from ancestor worship to that of the Birdman Cult (Nunn 2007).

Finally, over the last 250 years, sometime after European arrival on Easter Island in 1722 CE, the pollen record of Rano Raraku lake shows the direct and more intense influence of human activities, with the introduction of several taxa (e.g., P. guajava, *Eucalyptus* sp.) and the disappearance of indigenous plants such as *Sophora toromiro* (Cañellas-Boltà et al. 2013).

6 Hydrogeology

6.1 The Nature of Easter Island Aquifers and Water Recharge

Most young volcanic islands are formed of highly porous and fractured volcanic rocks which determine an almost total absence of permanent surficial streams and springs (Falkland 1993), favoring the formation of basal aquifers. Easter Island is characterized by just such a basal aquifer in the lava flows beneath the Terevaka volcano.

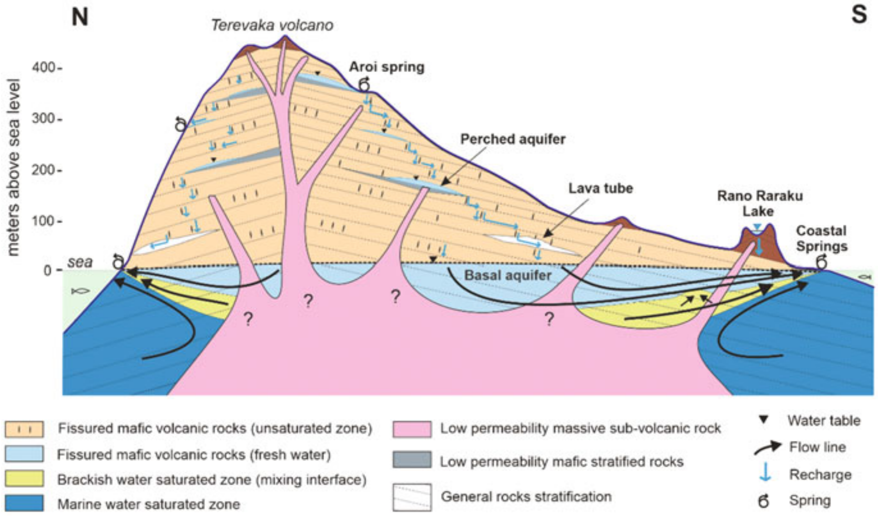

Fig. 13.6 Schematic showing a conceptual hydrogeological model for Easter Island. The vertical scale is only valid for the subaerial topography of the model

The presence of highly porous/permeable pyroclastic levels interbedded between less porous/permeable but fissured lava flows gives a greater anisotropy and heterogeneity to the aquifer system. Also, the increased aquifer permeability created pathways for groundwater flow from lava tube cavities below the water table. In some sectors near the volcanic centers, the aquifer is composed of massive volcanic rocks and hydrothermally altered low permeability rocks. This could explain the origin of wetlands in the bottom of some of the craters such as Rano Raraku, Rano Kao, and Rano Aroi (Fig. 13.6). The persistence of these water bodies was likely aided by the rapid accumulation of fine sediments and organic matter, which reduced permeability in the crater basin.

Recharge on Easter Island occurs through rainwater infiltration and was calculated by means of chloride balance in the soil in a steady state (Custodio 2019). Considering the marked altitudinal variability of the rainfall recorded on the island, an equally significant difference can be expected in the values of natural recharge to the system (Puleston et al. 2017). Monitoring of the chemistry of the rainwater coupled with sampling of the recharge water (Herrera and Custodio 2008) indicates that recharge is around 800 mm/year at higher elevations and in the order of 300 mm/year in the lowlands.

6.2 Conceptual Hydrogeological Model of Easter Island

Groundwater on Easter Island is an unconfined aquifer which receives significant volumes of recharge with natural discharge occurring along the coast. As such, groundwater moves according to the topographic surface contours of the island. This groundwater flow is radial and flows from the highest points towards the sea (Fig. 13.6). Geophysical profiles indicate that the island aquifer consists of a thin lens with a saline interface whose upper limit is between approximately 2 and 40 m above sea level (Tapia 2019). This shows that this aquifer is a thin and freshwater lens. Considering that short-term sea-level variations such as tides and storms have values less than a few meters in this area of the Pacific Ocean (Alamos and Peralta 1992), we can conclude that these variations do not influence the springs' discharge along the coast. Additionally, the high permeability and recharge values indicate that groundwater moves fast from the recharge zone to the sea. The relatively rapid flow of groundwater from the recharge to discharge zones is evidenced by the presence of tritium in the deep wells sampled on the island (Herrera and Custodio 2008). The low variability in the springs would also indicate that the system and the saline interface are possibly in steady-state conditions over a relatively short-time.

The high recharge values suggest that the aquifer has a high permeability since the hydraulic gradient is not elevated as in other volcanic areas of lower permeability. Interpretations of pumping tests at the time of low-penetration well construction on the coast of this island indicate transmissivity values between 20,000 and 40,000 m^2/day (Alamos and Peralta 1992). These high values of transmissivity correspond to the first saturated meters. They suggest permeability values higher than 4000 m/day, considering the saline interface depth estimates for recent volcanic formations. The low number of springs on Easter Island, considering the high recharge values, suggests a minimum of low permeability volcanic rocks. However, in the Rano Kao and Rano Raraku volcanoes, there are lakes that contain water several meters deep located several meters above the island's phreatic level. The wetland of Rano Aroi, near the top of the Terevaka volcano, is associated with a small stream that corresponds to a perched aquifer. Thus, it is possible that several other small aquifers are perched in the volcanic structure of the Terevaka volcano not forming springs, and whose discharge finally continues its vertical downward path towards the main basal aquifer (Fig. 13.6).

A significant number of brackish discharge points can be seen at low tide on the coastal edge of Easter Island (Brosnan et al. 2018). These brackish discharge points correspond to the discharge of water from the basal aquifer. These sea-level springs show tidal influences, and their chemical composition is a mixture of fresh and salt water (Fig. 13.6). Easter Island's model of frequent springs on the coastal edge contrasting with scarce springs at higher elevations has also been recognized in other young volcanic islands in the Pacific such as the Kilauea volcano aquifer in the Hawaiian archipelago (Ingebritsen and Scholl 1993). Although the waters of the coastline are slightly more saline because of mixing with water from the saline interface, its chemical composition is suitable for human consumption. Furthermore, its main island aquifer origin helps to eliminate pathogens that are characteristic of surface lakes in tropical and subtropical climates.

6.3 Potential Changes in the Aquifer Recharge During Deforestation and Drought Periods in the Past

The main characteristics of the present hydrological model for Easter Island described above can be assigned to hydrological conditions for the last 1000 years of the history of the island. However, two aspects related to the volume and salinity of the basal aquifer recharge water need to be considered, although they are poorly quantified (see Sect. 5): (1) droughts during the MCA and LIA and (2) intense deforestation since human occupation of the island over the last few centuries.

The potential effect of past climatically driven droughts on Easter Island aquifer is difficult to evaluate because of uncertainty of the permeability values. In complex and poorly characterized groundwater flow systems, Lumped Parameter Models are often used to estimate the mean transit time of the water in the aquifer (Maloszewski and Zuber 1982; Jodar et al. 2016). Herrera et al. (2004) assessed the average residence time of water in deep boreholes of the aquifer and compared the tritium contents with those of rainwater that was sampled monthly at the Easter Island and Cook Islands stations since 1963 (the Cook Islands dataset is one of the oldest in the South Pacific) (IAEA 2003). The models showed that renewal of the water in the aquifer varies between 5 and 70 years. This data suggests that even in the extreme case that the recharge had been very low as a consequence of severe and prolonged drought, the residual flow of water stored in the basal aquifer would have fed permanent springs on the coast for a long period of time, perhaps tens of years, thus reducing the impact of droughts on the volume of the aquifer.

On the other hand, deforestation probably contributed to an increase in the recharge of the basal aquifer by decreasing evapotranspiration, as is recognized in many other cases (Ruprecht and Schofield 1991; Cañedo-Argüelles et al. 2013). This increase in the recharge rate implies a washing of the salts present in the soil and in the unsaturated zone that could increase the salinity of the water discharged in the springs. Thus, deforestation has a negative effect on the quality of the groundwater by significantly increasing (up to 40 times) the salinity of the water as demonstrated by Ruprecht and Schofield (1991). The effects of increased groundwater salinity can last from tens to hundreds of years until the initial conditions of the aquifer system are restored. This water salinity increase might have adverse consequences on crop yields as it can affect the growth of some plants due to their differential tolerance to saline water (Zhao et al. 2020 and references therein).

Therefore, the short- and long-term consequences of the interplay between climate fluctuations and anthropic deforestation on aquifer recharge and water quality are far from evident. However, both forcings must have played a key role on past agricultural practices through changes on water availability on the island.

7 Tsunamis

7.1 *Large Polynesian Tsunamis During Late Holocene*

There is a growing body of evidence for three region-wide prehistoric earthquakes and their associated tsunamis within the region (Fig. 13.7). These most likely originated from the Tonga Kermadec trench (TKT) around 2800–3000 years BP (Fig. 13.7a), about 2000 years BP (Fig. 13.7b) and 1450–1500 CE (hereafter termed "mid-fifteenth-century") (Fig. 13.7c) during the time of Polynesian settlement (Goff et al. 2011, 2012a). In addition to these events generated "within" the South Pacific, there are other known Pacific-wide paleotsunamis that have affected this region. Most notable are those generated by subduction earthquakes associated with the tectonic boundary between the Nazca and South American Plates off the coast of Chile. While those associated with the TKT would approach Easter Island from the West, these would approach from the East/South-East. In a deeper time context, recent work in Chile has highlighted numerous paleotsunamis dating back at least 5000 years, with events over the past 1000 years dated to around 1100 CE, 1350 CE, and 1450 CE (refer to Goff et al. 2020 for further details). The effects of such large potentially Pacific-wide tsunamis have been shown to have been catastrophic for coastal Polynesian people with the loss of coastal resources (shellfish, littoral crops), loss of long-distance voyaging canoes, high death tolls particularly among the elderly and infirm (often the keepers of important traditional knowledge), the increase of warfare and the movement of communities inland and uphill (for an overview of the effects on New Zealand Maori, see McFadgen and Goff 2007).

7.2 *Tsunamis Evidence and Societal Effects in Easter Island*

From geological and historical research, we know that up to as many as 50 earthquakes capable of producing tsunamis affecting Easter Island occurred over the past 1000 years (Margalef et al. 2018). This includes the major precursor event to the 1960 Chile tsunami that occurred in 1575 CE and the large mid-fifteenth century paleotsunami discussed above. Both these events are worth considering within the chronology of human settlement and cultural change on Easter Island.

In addition, an Easter Island oral tradition states that the god Uoke is said to have to prised pieces off the volcanic cliffs with a giant crowbar until it broke on the hard rocks at Puko Puhipuhi. Such potentially tsunamigenic slope failures (TSFs) off the sides of volcanic edifices are remarkably common in the Pacific, although they are rarely recorded and as such represent only about 14% of all known events (Gusiakov 2009; Goff and Terry 2016). Given the focus on tsunamis generated by subduction zone earthquakes it seems highly likely that the lack of reporting of TSFs, coupled with a limited amount of research on these source mechanisms means that many

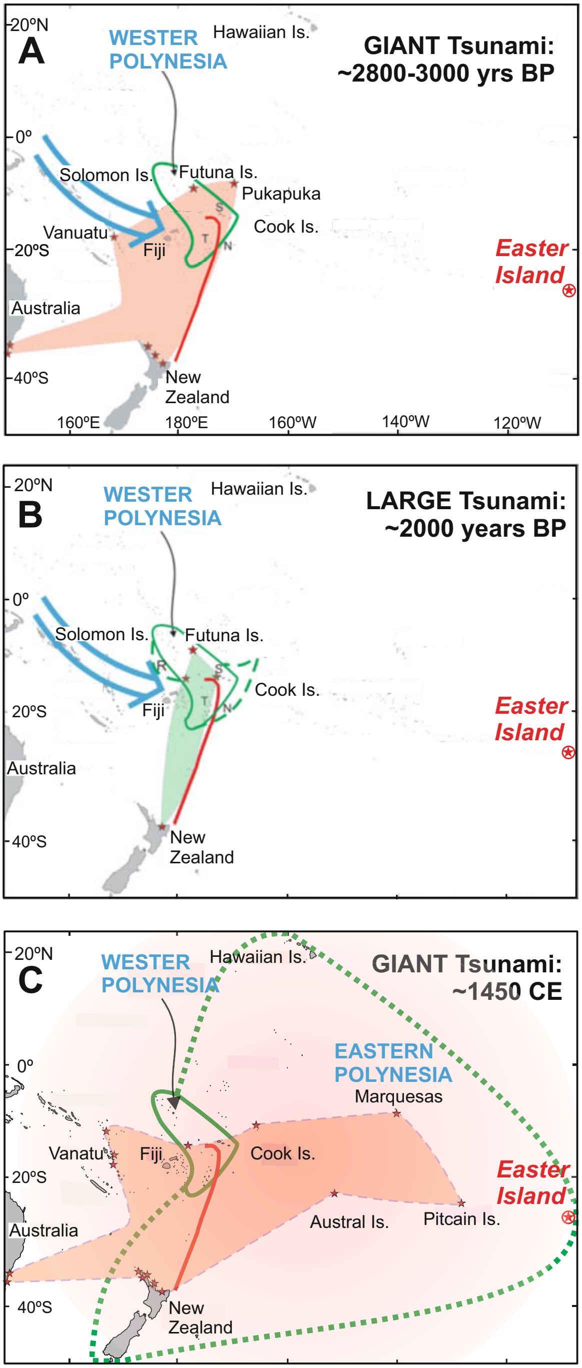

Fig. 13.7 Maps of South Pacific corresponding to three periods recording earthquakes and associated tsunami activity. Blue arrows indicate Polynesian settlement, green lines outline extent of western and eastern Polynesia, red line approximates the seafloor extent of the Tonga Kermadec Trench, orange and green shaded areas show known extent of paleotsunami evidence (refer to Goff et al. 2011, 2012a, b for details), gradational pink shaded area in C indicates inferred extent of one or more after-effects related to the mid-fifteenth century earthquake and paleotsunami

small to large local and regional tsunamis are missing from the history of Polynesian settlement, and Easter Island in particular.

The existing archeological debate as to what happened to Easter Island's prehistoric Polynesian culture still fails to consider the impact of tsunamis. And yet geological and archeological evidence exists for a region-wide catastrophe throughout Polynesia in the fifteenth century and even on the island there is archeological evidence of demographic decline and cultural change. As noted above, this is one of the social change indicators associated with the after-effects of paleotsunami inundation (Goff and Nunn 2016).

Notwithstanding these possible clues of prehistoric tsunami inundation, there is considerable historical evidence for the 1960 Chile tsunami devastating the island's eastern coastline. Here the waves destroyed the famous Ahu Tongariki, with estimates of waves exceeding 10 m in height and a run-up in the order of 1 km inland towards the base of the Raraku volcano (Domínguez, 1961; Cortez et al. 2009). In comparison, the 2010 Chile tsunami only ran up to the foot of the Ahu (Fritz et al. 2011). In 1960, the Ahu on which *moai* had stood was completely destroyed and several *moai* weighing up to 50 tons were carried more than 150 m inland (Cristino and Vargas Casanova 1999). Inland of the *ahu*, the whole area was littered with tsunami boulders, dead sheep, ripped-up seaweed, fish, and human bones from the tombs that had been under the Ahu (Anon 2021).

It is worth remembering that long before the 1960 tsunami the statues had been toppled and the *ahu* abandoned (Cristino and Vargas 2002). It is in this phase of Ahu Tongariki that it is possible to identify possible clues of the devastating effects of one or more paleotsunamis. What would an earlier event of similar or greater magnitude to the 1960, and from a similar source, have done to the then coastal population, monumental architecture, and resources? There have been several large historically documented events to have at least reached the island. The most important event is probably the 1575 CE precursor to the 1960. The confluence of indirect evidence here—cultural change, population decline, inland migration of main settlements, and destruction of the *ahu*—points towards the possible devastating effects of the 1575 CE tsunami on Ahu Tongariki. The chronology of cultural change on the island appears to occur around this time, but also earlier evidence for the mid-fifteenth century tsunami throughout the wider South Pacific suggests that such social upheaval and loss of monumental architecture may have been repeated over the centuries. Indeed, it has been proposed that some *ahu*, made of ancient, recycled *ahu* remains and fragments of marine material, may indicate the impact of more than one paleotsunami (Cortez et al. 2009).

Past tsunamis might have locally affected coastal soils as shown the 2011 Japan tsunami (Chagué-Goff et al. 2014). When tsunamis occur, soils that are not eroded by the strong flows are rapidly buried by marine and terrestrial sediments. In this case, plants often die, and the soils undergo extensive salinization. While these extreme events can introduce nutrients to coastal soils although any potential benefits are invariably outweighed by the previously stated negative side effects. In the case of Easter Island, more data on the extent and occurrence of tsunami deposits would be necessary to assess their impact on the ancient society.

7.3 The Reach of Past and Present Meteotsunamis

Another form of tsunami, the meteotsunami, offers yet another layer of complexity to the Easter Island story. As defined by Defant (1961), a meteotsunami is essentially a seiche of a bay or the shelf, but it differs in that it exceeds the amplitude of a normal seiche (a seiche is a temporary disturbance or oscillation in the water level of a lake or partially enclosed body of water, mostly caused by rapid changes in atmospheric pressure and/or strong winds—these can last for hours or even days), with Monserrat et al. (2006), Rabinovich (2020), and others setting the amplitude threshold at four standard deviations (4σ). In a recent 17-month long study of sea-level readings from the Hanga Piko Harbor tide gauge on Easter Island, Carvajal et al. (2021) recorded dozens of seiches that fitted this criterion, but because they were unclear of the precise forcing and resonant processes driving these events preferred to call them "intense seiches" as opposed to meteotsunamis. The most extreme of these occurred on March 5th and May 5th, 2020 and tripled the high spring tide, at +1.1 m and +1.3 m above MSL, respectively. Such events are probably best described as "bad weather" meteotsunamis (Rabonivich 2020), but while there may be some debate over their designation, they are interesting in the context of cultural change and the effect they might have had on the prehistoric Polynesian settlers. Since the magnitude of these events is intimately tied to meteorological and oceanographic processes it would seem reasonable to suggest that a better understanding of past conditions may help us better understand the implications for the human population, not least of which would be on the supply, abundance, and access to essential marine resources.

8 Conclusions

Intrinsic geological features of Easter Island as volcanic nature and geomorphology, abrupt regional geological processes such as earthquakes and tsunamis, and short- and long-term climate fluctuations, through independent processes or those dependent on others, significantly influenced the life of the inhabitants of this tiny island since its occupation at the beginning of the last millennium. Their effects on the population were "positive"—"constructive," "negative"—"destructive" or simply not significant at all depending on if they promoted or hampered both short- and long-term survival of Easter Island inhabitants (Fig. 13.8).

Plate tectonics and derived volcanism in this oceanic region were responsible forces for the birth and growth of Easter Island, creating an emerging land capable of being colonized in the middle of the Pacific Ocean. The volcanism conditioned the topography of the island and created the land support for the development of the hydrogeological model, the paleoenvironmental processes, the oceanic dynamics that surround the island and, ultimately, the human settlement on it.

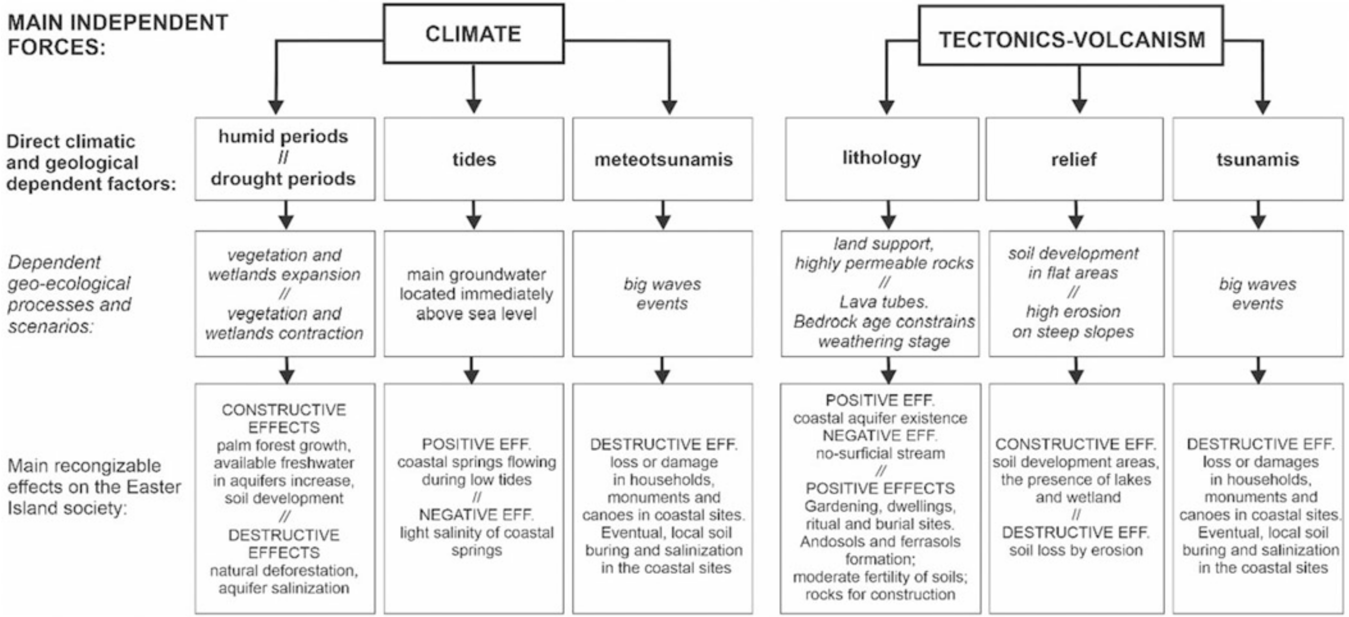

Fig. 13.8 Effects of physical factors and processes on occupation and habitation of Easter Island society. Factors and processes have been separated by those mainly controlled by climate and those by volcano-tectonic forces. Note the consideration of constructive, destructive, positive and/or negative effects of each geo-ecological scenario (see text for more explanation)

The hydrogeology of Easter Island would guarantee the continuity of freshwater supply for human consumption even during drought periods, especially in the inland lowlands. Paradoxically, the decrease in evapotranspiration rate caused by major deforestation phases would compensate for the loss of aquifer recharge during the MCA and LIA dry periods, although the water salinity would significantly increase, and probably diminishing the water quality. The access of most of the population to freshwater through wells and natural springs in lowlands of the island made it possible to rule out the use for human consumption of less healthy and inaccessible water from the crater lakes of Rano Raraku and Rano Kao, as is still the case today. Overall, the hydrological system of Easter Island can be considered as a positive factor for the island habitants, probably scarcely constrained by climate and which largely determined the spatial distribution and agrarian activity of the islands population. However, a more careful assessment on this topic would be needed.

The cultivable soil on Easter Island, although with only moderate fertility, had two important limitations. First, shallow depth due to the youth of the island's formation and its difficulty in retaining moisture due to the permeability of the substrate and of the soils themselves. However, the intensive development of gardening throughout the island except in the Poike sector partially alleviated this last problem. Second, the erosion of cultivated soils was a growing problem for the prehistoric inhabitants of the island due to the subsequent deforestation episodes. The loss of soil has been aggravated in recent times by the presence of livestock on the island. Therefore, the progressive loss of cultivated soils must be considered as a negative factor that hampered the development of Easter Island inhabitants.

High-energy geological and climatic phenomena such as tsunamis and storms occurred with some frequency, influencing the imagination/religion of its inhabitants during prehistory and promoting the construction of *moai* and their placement on the seafront. Hence, while these catastrophic short events had negative consequences for the inhabitants of the island due to their high destruction capacity, especially for the coastal lowland areas, it is very difficult to assess their influence in the long-term run. In contrast, and in spite of the recognizable geological elements on Easter Island, the lakes and volcanoes were passive landscape elements that, in the absence of a literature on the matter, appear to have had no special spiritual consideration for the Easter Island culture.

This work emphasizes the importance of the intrinsic geological features as well as the main geological and environmental processes that shape a given place when colonized. These features and processes should be considered when analyzing the evolution of human occupation of a given area, especially of remote islands.

Acknowledgments AS, OM, SP-R, SG research was funded by the Spanish Ministry of Education and Science, through projects LAVOLTER (CGL2004-00683) and GEOBILA (CGL2007-60932/BTE). LB research has been funded by ANID through the Fondecyt Postdoctoral grant 3180257. LEL research has been funded by ANID (Chile) through Fondecyt projects 1141303 and 1211792 and Fondap 15110017. We want to thank R.K. Dunn and Ch. Stevenson for the constructive revision of a first draft of this chapter.

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Part IV
Deforestation and Extinctions

Chapter 14
The Flora and Vegetation of Easter Island: Past and Present

Georg Zizka and Alexander Zizka

1 Introduction

The floristic inventory of a region can be divided into two groups based on immigration history: native species that evolved in situ or arrived via dispersal without human action and introduced species that occur in an area due to human impact (Richardson et al. 2000). Introduced species may have arrived by direct human transport of diaspores or depend on the creation of suitable habitats by humans. For the analysis of biogeographic relationships and the reconstruction of past vegetation, only the native species are of interest. On Easter Island, the identification of native species is challenging, because of the high human impact for a long time, and the resulting high number of introduced species and putatively extinct native species in the present-day flora. Palynological and archeological studies can provide direct evidence of the presence of species before human arrival, yet are often incomplete. In the absence of sufficient direct evidence, analyses of the distribution and ecology of recent species can provide circumstantial evidence for the reconstruction of the native flora and its ecological preferences.

Numerous attempts to reconstruct the native flora of flowering plants of Easter Island exist (Skottsberg 1922, 1928, 1953, 1956; Guillaumin et al. 1936; Etienne et al. 1982; Etienne and Faundez 1983; Flenley and King 1984; King and Flenley 1989;

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_14

Zizka 1990, 1991; Flenley et al. 1991; Orliac 1998; Butaud 2006; Azizi and Flenley 2008; Butler and Flenley 2010; Dubois et al. 2013; Rull 2020). Most of these authors agree that the current flora and vegetation of the island are the product of intensive human impact over centuries, driving native species to extinction and introducing species from other parts of the world, many of which have become naturalized or invasive. In addition, recent studies point toward the role of Quaternary climatic changes in the depletion of the flora and vegetation of Easter Island (Cañellas-Boltà et al. 2013; Rull et al. 2010, 2015).

Here we provide an updated, commented list of angiosperms, ferns and fern allies, mosses, and liverworts putatively native to Easter Island (see Appendix) based on a review of the existing literature, and assess the biogeographic relationships of these species. We emphasize the differences in biogeography between angiosperms and the other groups of terrestrial plants, because, in contrast to angiosperms, ferns and fern allies, mosses, and liverworts are rarely found to be introduced and thus may be more informative on the biogeographic affinities of the native island flora. We make use of publicly available distribution data and of the concept of ecoregions (Olson et al. 2001) to extract information about the biogeographic relationships of the native flora of Easter Island.

2 The Present Flora of Easter Island

Comprehensive inventories of the flora of Easter Island exist for the major groups of terrestrial plants (seed plants, ferns and fern allies, mosses, and liverworts), which form the basis of this contribution (mosses sensu lato: Brotherus 1924, Theriot 1937, Ireland and Bellolio 2002, Grolle 2002, Müller 2009; ferns and fern allies: Christensen and Skottsberg 1920, Guillaumin et al. 1936, Godoy and Figueroa 1989, Looser 1958, Baeza et al. 1998, Butaud 2006, Meyer 2013; angiosperms: Skottsberg 1922, Etienne et al. 1982, Etienne and Faundez 1983, Zizka 1991, Butaud 2006, Finot et al. 2015, Dubois et al. 2013).

Our list of putative native species comprises 33 moss taxa (Bryophytina; Ireland and Bellolio 2002; Müller 2009) and 11 species of liverworts (Marchantiophytina, Grolle 2002). Three species of mosses are endemic to the island (none of the liverworts). There is no information about introduced species available for mosses so we assume all species to be native to Easter Island. One sterile species of hornwort (Anthocerotophytina) is documented but remains unidentified (Grolle 2002), and we therefore do not consider it here.

Our list comprises 21 native fern and fern allies taxa. Of these, 16 species were reported by Meyer (2013), including 13 species in the subclass Polypodiidae (true ferns, both Polypodiopsida) and 3 in the subclass Ophioglossidae (genera *Ophioglossum, Psilotum*). Additionally, the genera *Lycopodium, Huperzia* (both Lycopodiopsida), *Cyathea, Hymenophyllum*, and *Pteris* (Polypodiopsida) were recorded on the island based on spore records without identification to species level

(Azizi and Flenley 2008; Butler and Flenley 2010; Horrocks et al. 2015; Rull et al. 2015). All of these fern and fern allies species are putatively native. In addition, Meyer (2013) observed four introduced fern species, cultivated in gardens in the village Hanga Roa. One of these species, *Cyclosorus* cf. *parasiticus*, was observed also outside cultivation. However, its status of naturalization is unclear and we therefore do not consider it here.

Our list comprises 33 native seed plant taxa in the present-day flora, excluding the extinct *Paschalococos disperta* and corresponding to 18.4% of the 179 species growing outside cultivation reported by Zizka (1991) (Figs. 14.1 and 14.2). One native species, *Sophora toromiro*, is surviving only in cultivation. No native gymnosperm species are known from the island (although Butaud 2006 mentions seven introduced and cultivated species); hence, seed plants are only represented by angiosperms. The high number of introductions, together with increasing tourism and traffic/trade—as in all parts of the world—results in the increase of alien species, which occur outside cultivation and may become naturalized or even invasive (Fig. 14.3). Due to the continuously ongoing introduction of new species (e.g., Fig. 14.3), the total number of naturalized species on Easter Island has increased since 1991 (Butaud 2006; Dubois et al. 2013; Meyer 2008; Finot et al. 2015). New additions to the flora since 1991 mostly include cultivated species and cosmopolitan weeds associated with human settlements and disturbed habitats worldwide, such as *Asclepias curassavica*, *Cortaderia selloana, Cenchrus clandestinus, Triticum aestivum,* and *Zea mays*. The species list of Butaud (2006) comprises 437 species (18 ferns and fern allies, 7 gymnosperms, 412 angiosperms), including 351 species that were introduced after 1722, of which many are found exclusively in cultivation.

Further updates of the species list presented here compared to Zizka (1991) result from taxonomic revisions and nomenclatural changes. Specifically, Finot et al. (2015) in their treatment of the flora of Easter Island rely on the revision of *Eragrostis* in Chile by Escobar et al. (2011), which regard the records of *E. leptostachya* and *E. spartinolides* in Zizka (1991) as misidentifications and place the investigated specimen Zizka 1541 in *E. atrovirens* (Escobar et al. 2011). Furthermore, *Boerhavia acutifolia* is recognized as a native species instead of subspecies *Boerhavia diffusa* var. *acutifolia* of the widespread *B. diffusa* (Dubois et al. 2013). Finally, progress in taxonomic research has led to changes in genus delimitation resulting in nomenclatural changes, e.g., the transfer of the endemic species *Danthonia paschalis* to the new genus *Rytidosperma (R. paschale*; Baeza 1991) and the placement of the prominent Totora in *Schoenoplectus* (*Schoenoplectus californicus* instead of *Scirpus c.*; Figs. 14.1 and 14.2).

In the Appendix, we provide a list of the accepted scientific names of all taxa of angiosperms, fern and fern allies, mosses, and liverworts which are discussed to be native on Easter Island based on the GBIF Taxonomy backbone (see URL: https://www.gbif.org/dataset/d7dddbf4-2cf0-4f39-9b2a-bb099caae36c). Furthermore, we provide synonyms, native distribution according to Kew Plants of the Worlds Online (POWO; http://www.plantsoftheworldonline.org/), and literature references.

Fig. 14.1 Crater Lake of Rano Raraku with a large stand of Totora (*Schoenoplectus californicus*) and obvious erosion marks on the slopes

Fig. 14.2 Two prominent native species of Easter Island: Totora (*Schoenoplectus californicus*) and Tavari (*Persicaria acuminata*)

Fig. 14.3 In vast areas, the vegetation is dominated by introduced species. Here, at the foot of Rano Raraku, *Cirsium vulgare*, *Psidium guajava*, *Crotalaria pallida, Asclepias curassavica*, and *Macroptilium lathyroides* are abundant species

The described spread of human introduced invasive species poses pressure on the remaining native flora. Multiple conservation projects aiming at propagating native species, protecting their habitats, and removing invasive species exist (e.g., Zizka 1993; Meyer 2008; Dubois et al. 2013). Yet, as tragically illustrated by the so far unsuccessful attempt to reintroduce the iconic Toromiro (*Sophora toromiro*), the changes in vegetation, fauna, soil conditions, and probably in genetic diversity are a substantial hurdle to these conservation efforts, even if sufficient plants for reintroduction are available (Maunder et al. 2000).

3 The Flora of Easter Island Before the Arrival of Humans

The natural history of Easter Island, in particular its native flora and vegetation, has received great scientific attention, since it provides the basis for the development of the islands' human population and the iconic Moai and Birdman cultures. It had long been postulated that Easter Island is currently exceptionally poor in native plant species (van Balgooy 1971). Only later studies provided scientific documentation that this flora, as already encountered by the first Europeans in the eighteenth century, was only the depauperate remainder of a once more diverse set of species (Flenley and King 1984; Flenley et al. 1991; Flenley 1993a, b, 1996). Since then, the reconstruction of the original biodiversity of the island has profited in particular from palynological and archeological studies.

First, paleoecological studies based on pollen cores from lakes in the three island volcanos Rano Kao, Rano Raraku, and Rano Aroi provided the first evidence for once existing large forests, and added taxa to the native plant diversity before the arrival of humans (e.g., members of the genera *Acalypha, Metrosideros, Potamogeton, Typha*; Flenley et al. 1991). However, the reconstruction of flora and vegetation based on palynological evidence has limitations. Most importantly, taxon identification is relying on diacritic characters in pollen or spore morphology often limiting identification to higher taxonomic levels, yielding identifications such as "palm", "Urticaceae/Moraceae", "Asteraceae-Tubiflorae", "*Coprosma*", and others. Furthermore, the amount of pollen produced differs largely among wind- and animal pollinated species. Hence, a lack of pollen, especially from animal pollinated species, does not rule out a former occurrence on Easter Island. In the "transitional" and "revival phase" of Easter Island research (Rull 2020), new paleoecological and archeological evidence added taxa to the list of native Easter Island species. For instance, the analysis of fossil palm phytoliths has provided evidence for other palm (Arecaceae) species besides *Paschalococos disperta* on Easter Island (Orliac and Orliac 2008; Delhon and Orliac 2010; Gossen 2011; Bowdery 2015).

Second, archeological studies of charcoals and the wood anatomy from dwelling sites and of artifacts (e.g., carvings; Orliac 1998, 2000, 2007) provided insights into the flora of Easter Island before the arrival of the Europeans. However, these records are dated to the time after the arrival of humans, and it cannot be excluded that charcoal or artifacts originated from driftwood. Thus, the wood anatomical data in our opinion do not necessarily provide information about flora and vegetation before the arrival of humans. Butaud (2006) provides a comprehensive review on the flora of tracheophytes (ferns and fern allies and seed plants) of Easter Island, estimating the number of native species between 63 and 68 and providing a list of 68 native species.

In addition to the direct evidence from paleoecological and archeological studies, the botanical investigation of the current flora from collections, historical documents, and scientific literature can provide circumstantial evidence for the identification of native species, although limited in time to the oldest collections and scientific reports. Taking distribution, dispersal abilities, and ecology into consideration allows for an assessment of the present flora and its immigration history.

Our list of putatively native angiosperm species (Appendix) includes 20 taxa that have been recorded in paleoecological studies and mostly dated to before human arrival. We also included records only identified to genus and family level (the latter not included in the biogeographic analysis). For the recorded representative of the genus *Capparis*, we regard the native status doubtful and excluded it from the biogeographic analysis. The following taxa have also been added to the list, but for various reasons we did not include them in the biogeographic analysis (for more details, see Appendix): (1) Two taxa (*Santalum* spec., *Sesuvium portulacastrum*) reported in the literature without underlying herbarium specimens or pollen records. (2) Six palm species. The occurrence of more than one palm species appears reliable from the phytolith studies, and, when following Gossen (2011), three additional palm species, and according to Bowdery (2015), even six palm species may have been native to the island. However, the number of palm species and their taxonomic relationships remain doubtful. (3) Orliac (1998, 2000, 2007) and Orliac and Orliac (2008) identified ten additional species from studies of charcoal and wood carvings. We regard the origin of these species as doubtful; for a human introduction or origin from driftwood cannot be excluded. In total, our list of angiosperm species for Easter Island comprises 70 taxa, of which 48 were included in the biogeographic analysis.

Van Balgooy (1969, 1971) included Easter Island in his geographically comprehensive studies on island plant diversity. Based only on the number of genera and families he suggested the plant diversity of the island to be exceptionally poor in relation to island area. Yet, van Balgooy underestimated the number of native families and genera of the island (15 and 22, respectively, van Balgooy 1969). Based on our list taking the pollen records and more recent publications into consideration, the native flora comprised at least 28 families and 48 genera. A different attempt to calculate the native angiosperm flora of Easter Island was published by Weigelt et al. (2013). In a modeling approach based on data from 17,883 marine islands worldwide and considering area, climate data, elevation, isolation, and past connectivity, they proposed a hypothetical vascular plant species number of 67.42 (standard error ±20.16) for Easter Island (Weigelt et al. 2013; Kreft et al. 2008), which fits well with the here listed 69 species (48 angiosperms, 21 ferns and fern allies).

4 From Distribution to Biogeography and Ecoregions

Various authors dealing with Easter Island´s plant diversity have analyzed the global distribution of putatively native species in order to characterize the biogeographic relationships of the island. However, such analyses have been almost exclusively restricted to angiosperms. Here, we integrate all groups of land plants (mosses, liverworts, fern and fern allies, and seed plants) with the aim to identify potential source areas and global ecoregions similar to the initial vegetation of the island. We use distribution information from the Global Biodiversity Information Facility (GBIF 2021) accounting for quality issues, by only retaining records with occurrence status "present," removing fossils, material based samples, non-native entries, as well as issues flagged with common geo-referencing errors when possible (Zizka et al. 2019, 2020), and Plants of the World Online (POWO; URL: http://www.plantsoftheworldonline.org/), the latter providing only information for angiosperms and ferns and fern allies. GBIF and POWO provide different types of data. While GBIF contains geo-referenced localities of species occurrences, POWO provides a list of geographical regions ("Botanical countries", usually at the scale of countries or provinces in the case of large countries, e.g., New Guinea, Queensland, or Bolivia), for which the species is considered native. While GBIF locality data are more precise, their completeness depends on the sampling effort across regions, which is often low, particularly on small archipelagos and islands. In contrast, POWO provides a relatively complete geographical coverage, but on a rough scale (regions).

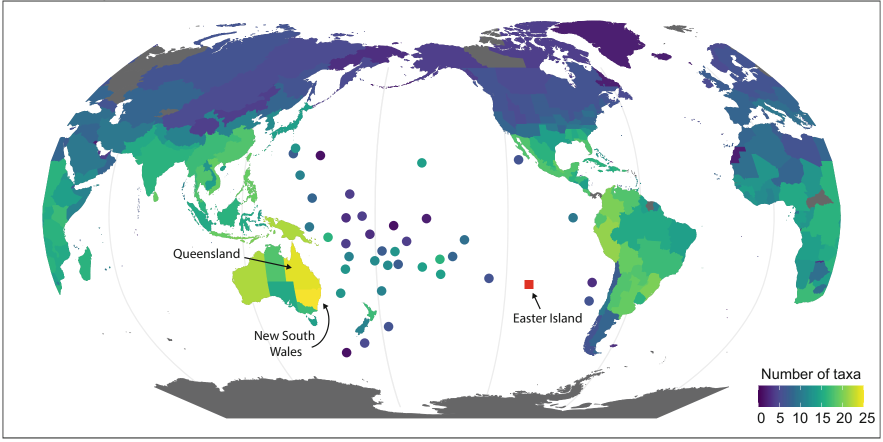
Looking at the POWO data first, for the angiosperms (Fig. 14.4a), based on 48 species, the strongest links of the flora of Easter Island are with Australia, SE Asia, and Oceania. Most native Easter Island species (and genera) occur also in New South Wales, Queensland, Western Australia, and New Guinea, followed by regions/islands/archipelagos from SE Asia, Oceania, and the Neotropics. Among the Pacific Islands, Society Islands, Solomon Islands, Cook Island, Samoa, and Fiji have most native species in common with Easter Island. However, 17 taxa are also distributed in Kenya, 16 in Madagascar, which makes clear that some of the species have a wide distribution. This holds especially true for the few genera included in the analysis based on pollen records (e.g., *Acalypha*), where no species could be identified. It is noteworthy that the biogeographic links to the Neotropics, especially northern South America, are stronger than those to parts of Africa and South Asia.

Looking at the fern and fern allies distribution (Fig. 14.4b; based on 21 species), the link to predominantly humid-tropical SE Asia, especially the Philippines and Lesser Sunda Islands, and to the Pacific Islands, especially Fiji, Samoa, Solomon, and Tubuai, is stronger than observed in the angiosperms, whereas the links to Australia and Oceania are less pronounced. Following the idea that fern and fern allies species have been less affected by direct human impact, this stronger SE Asian link may better reflect the relationships of the original flora and vegetation in the more humid periods in Easter Island history. Inaccessible localities like cliffs or parts of caves with sufficient light might have been micro-habitats for the fern and fern allies to survive putatively drier periods in the island's history.

For mosses and liverworts, no POWO data are available. Therefore, the following analyses are based on GBIF distribution data. In the mosses (Bryophytina; Fig. 14.5a), most Easter Island species are shared with (South) Eastern Australia and northern New Zealand. Less speciose links are with SE Asia and S and C America. In the liverworts (Marchantiophytina; Fig. 14.5b), (S)E Australia, mountainous parts of New Guinea, and parts of S America have the most species in common with Easter Island. Links to the remainder of tropical SE Asia are less prominent than in the mosses.

Ecoregions and biomes (Olson et al. 2001) provide an approach to use the recent floristic elements of Easter Island to approximate the past vegetation of the island. These ecoregions have been defined as biogeographic units primarily as a tool for conservation planning. However, they are built on the elements of classical biogeography like species diversity and endemism as well as environmental conditions and vegetation structure, and thus, we use them here to hypothesize about the original vegetation of the island. It should be noted that a species can be assigned

a Flowering plants



b Ferns & fern allies

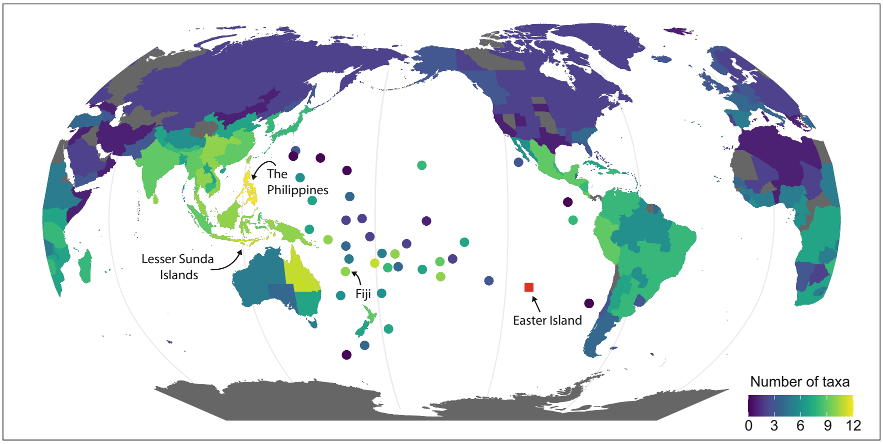
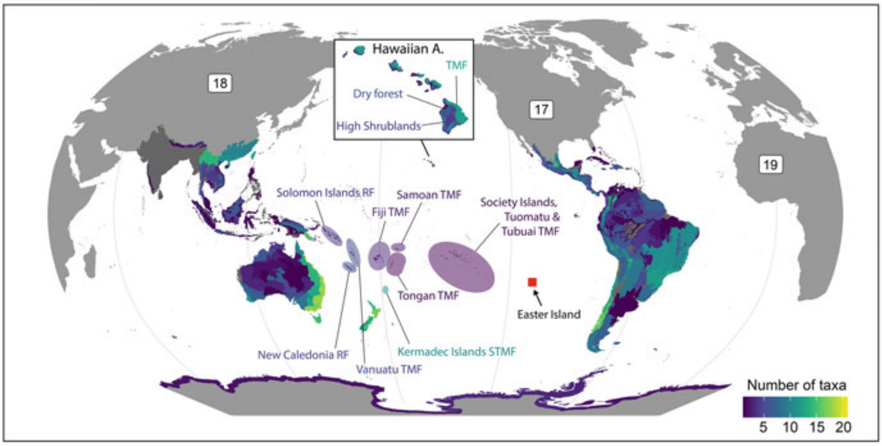
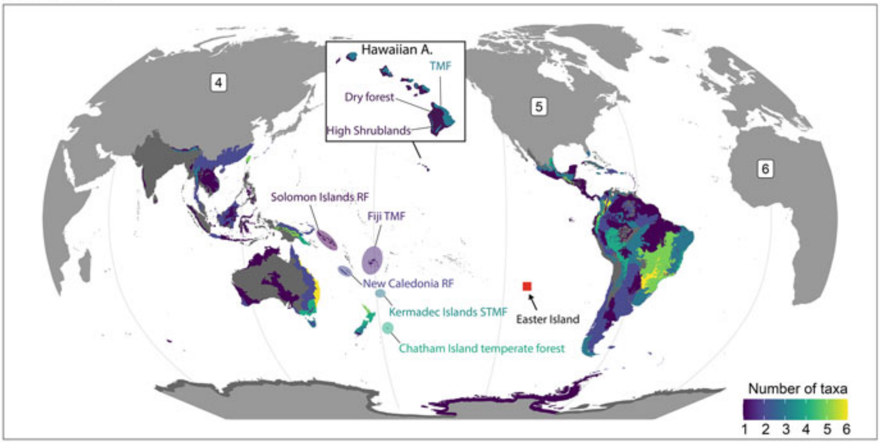


Fig. 14.4 Occurrence of putatively native Easter Island angiosperm and fern and fern allies taxa based on the distribution data given in Plants of the World Online (POWO). The color-coding indicates the number of taxa occurring in the areas defined by POWO. (**a**) Angiosperms ($n = 48$). (**b**) Ferns and fern allies ($n = 21$). The labels identify regions mentioned in the main text

to one, several, or many ecoregions depending on their range size (e.g., *Dicranella hawaiica* occurs in one ecoregion outside Easter Island, whereas *Bryum argenteum* occurs in 221). Figure 14.6 shows the number of species from the putatively native Easter Island flora that could be assigned to one or several of the altogether 867 terrestrial ecoregions worldwide, grouped into 14 biomes and 8 biogeographic realms (Olson et al. 2001). For angiosperms, ferns and fern allies, and mosses, a fairly similar picture arises: the ecoregions, where these Easter Island plants occur, are predominantly from the Australasia, Neotropic, and Indo-Malay realm, and are principally characterized by forest vegetation, and only rarely by savanna



a Mosses



b Liverworts

Fig. 14.5 Occurrence of putatively native Easter Island moss and liverwort taxa in the tropical and subtropical circum-Pacific area based on occurrence data from www.gbif.org. The color-coding indicates the number of taxa occurring in an area. Pacific archipelagos summarized by the shaded ellipses for readability. The Hawaiian archipelago is enlarged for readability. The numbers in squares refer to the number of Easter Island taxa occurring outside the relevant area. (**a**) Mosses. Number of taxa included: 29 (5 genera, 24 species). (**b**) Liverworts. Number of taxa included: 11 (1 genus, 10 species). *(S)TMF* (Sub-)Tropical Moist Forest, *RF* Rainforest

or grassland. In liverworts, the link to the Indo-Malay realm is less prominent, and stronger to S America. The strong dominance of species from ecoregions characterized by forest supports the idea of a forest-like original vegetation on Easter Island. Note that the weak biogeographic link to Oceania in the analysis of the GBIF data may be an artifact of low sampling density of records from Oceanian archipelagos.

Fig. 14.6 The number of taxa putatively native to Easter Island assigned to ecoregions (Olson et al. 2001) worldwide. The assignment is based on the available distribution data of the species from GBIF; one species can be assigned to one up to numerous ecoregions. Assignment is given for the studied group of land plants: angiosperms, fern and fern allies, mosses, and hornworts. The color of the bars refers to the biome regarded characteristic for each ecoregion. The abbreviations refer to the biogeographic realms recognized in Olson et al. 2001. *AA* Australasia, *AT* Afrotropic, *IM* Indo-Malay, *NA* Nearctic, *NT* Neotropic, *OC* Oceania, *PA* Palearctic. Ecoregions are ordered by total number of species; only the most important ecoregions are shown

5 Conclusion

The native flora of Easter Island remains incompletely known. Some species probably so far have not been detected at all, some still lack reliable evidence (e.g., *Santalum*), and others are only identified to genus or family level. Additionally, the reconstruction of immigration history (native vs. alien) in some cases is doubtful (e.g., *Capparis*). However, the number of vascular plants regarded native today (69 spp.) fits well with the number of expected native species based on environmental conditions, island size, orography, isolation, and distance to the next continent. Biogeographic analyses for angiosperms, ferns and fern allies, mosses, and liverworts confirm strong links to Eastern Australia, New Guinea, and Oceania with additional links to SE Asia and the Neotropics in mosses and liverworts. The distribution of native Easter Island species in ecoregions worldwide reveals a predominance of forest ecoregions, suggesting an important role of forests in past Easter Island vegetation. This does not contradict drier periods in the Easter Island history, which especially ferns and fern allies, mosses, and liverworts might have survived in suitable micro-habitats.

Acknowledgments We thank Holger Kreft for providing data about Global Island Biodiversity as well as all data providers to GBIF and the curators of POWO for their effort. Jean-Francois Butaud provided important comments and information. AZ is funded by iDiv via the German Research Foundation (DFG FZT 118), specifically through sDiv, the Synthesis Centre of iDiv. We are thankful to Christopher D. Barratt for linguistic proofreading.

Appendix

Commented list of putatively native angiosperm, fern and fern allies, mosses, and liverworts species recorded for Easter Island.

Taxon	Family	Status	Source	Synonym(s)	Remarks	Included in analyses
Flowering Plants (Magnoliopsida)						
Acalypha spec.	Euphorbiaceae	Native	Flenley et al. (1991)		Only genus documented by pollen records, no species identified. Native species are reported for French Polynesia (Chevilotte et al. 2019).	x
Adenanthera spec.	Fabaceae	Native	Azizi and Flenley (2008)		Only documented by pollen records.	x
Alphitonia zizyphoides A. Gray	Rhamnaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Apium prostratum Labill. ex Vent.	Apiaceae	Native	Zizka (1991)			x
Axonopus paschalis (Stapf) Pilg.	Poaceae	Endemic?	Zizka (1991), Finot et al. (2015)	*Axonopus compressus* (Sw.) P. Beauv.	Originally described as endemic *A. paschalis*. In recent revision (Finot et al. 2015) sunk in widespread *A. compressus*, but this view not generally accepted	x

Bidens spec.	Asteraceae	Native	Butler and Flenley (2010)		Only documented by pollen records, originally identified as Asteraceae-Tubiflorae. Identified to genus by Butler and Flenley (2010)	x
Boerhavia diffusa L. var. *acutifolia* Choisy	Nyctaginaceae	Native	Zizka (1991), Dubois et al. (2013)	*Boerhavia acutifolia* (Choisy) J.W. Moore; *Boerhavia diffusa* L.	Taxonomic rank is doubtful, concepts range from synonym of *Boerhavia diffusa* to separate species *B. acutifolia*. GBIF gives distribution data for *B. acutifolia*, these distribution data are used here.	x
Bromus catharticus Vahl	Poaceae	Native	Zizka (1991)			x
Broussonetia papyrifera Vent.	Moraceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Butia odorata (Barb. Rodr.) Noblick	Arecaceae	Doubtful	Bowdery (2015)	*Butia capitata* Becc. var. *pulposa* (Barb. Rodr.) Becc.	Only documented by phytoliths. Hypothetical species (“best match” of phytoliths with recent species).	
Caesalpinia globulorum Bakh. f. & P. Royen	Fabaceae	Native	Zizka (1991), Butler and Flenley (2010)	*Guilandina major* (Medik.) Small *Caesalpinia major* (Medik.) Dandy and Exell	Pollen records of Butler and Flenley (2010) identified only to genus.	x
Calystegia sepium R. Br.	Convolvulaceae	Native	Zizka (1991)			x
Canavalia spec.	Fabaceae	Native	Butler and Flenley (2010), Cañellas-Bolta et al. (2013), Rull et al. (2015)		Only documented by pollen records.	x

Capparis spec.	Capparidaceae	Doubtful	Flenley et al. (1991)		Only documented by a pollen record from between app. 550 and 1000 B.P. Possibly introduced.	
Chrysogonum spec.	Asteraceae	Native	Flenley et al. (1991), Rull (2020), Butler and Flenley (2010)		Only documented by pollen records, identified as Asteraceae-Tubiflorae. The genus given is hypothetical, known from SE Polynesia.	x
Coprosma spec.	Rubiaceae	Native	Flenley et al. (1991), Orliac (1998), Butler and Flenley (2010)		Only documented by pollen records and charcoal, no species identified.	x
Cynodon dactylon (L.) Pers.	Poaceae	Native	Zizka (1991)			x
Cyperus brevifolius (Rottb.) Hassk.	Cyperaceae	Native	Zizka (1991)	*Kyllinga brevifolia* Rottb.		x
Cyperus cyperoides Kuntze	Cyperaceae	Native	Zizka (1991)			x
Cyperus eragrostis Lam.	Cyperaceae	Native	Zizka (1991)			x
Dianella spec.	Xanthorrhoeaceae	Native	Cañellas-Bolta et al. (2014)		Only documented by pollen from Rano Kao for 9.5–5.4 kyr B.P. Cañellas-Bolta et al. (2014) name *D. intermedia/adenanthera* as possible species and report the genus as widespread in the Pacific islands. Butaud (pers. comm.) regards *D. adenanthera* as the most probable species due to its wide occurrence in Polynesia.	x

Dichelachne crinita Hook. f.	Poaceae	Native	Zizka (1991)			x
Dichelachne micrantha (Cav.) Domin	Poaceae	Native	Zizka (1991)			x
Elaeocarpus rarotongensis Hemsl.	Elaeocarpaceae	Doubtful	Orliac (1998)	*Elaeocarpus floridanus* Hemsl.	Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Erythrina spec.	Fabaceae	Native	Butler and Flenley (2010)		Only documented by rare pollen records.	x
Euphorbia serpens Kunth	Euphorbiaceae	Native	Zizka (1991)			x
Gen. spec.	Ericaceae	Native	Rull et al. (2015)		One pollen record from app. 800 BP (Rull et al. 2015), introduced?	
Gen. spec.	Moraceae	Native	Azizi and Flenley (2008), Butler and Flenley (2010), Rull et al. (2015)		Only documented by pollen records, in Butler and Flenley (2010: fig. 1) as “Urticaceae/Moraceae”	
Gen. spec.	Urticaceae	Native	Butler and Flenley (2010), Horrocks et al. (2013)		Only documented by pollen records	
Heterospathe longipes (H.E. Moore) Norup	Arecaceae	Doubtful	Bowdery (2015)		Only documented by phytoliths. Hypothetical species (“best match” of phytoliths with recent species).	
Howea belmoreana (C. Moore & F. Muell.) Becc.	Arecaceae	Doubtful	Bowdery (2015)		Only documented by phytoliths. Hypothetical species (“best match” of phytoliths with recent species).	

Ipomoea pes-caprae (L.) R. Br.	Convolvulaceae	Native	Zizka (1991)			x
Lachnagrostis filiformis Trin.	Poaceae	Native	Zizka (1991)	*Agrostis avenacea* J.F. Gmel.		x
Lycium carolinianum Walter var. *sandwicense* (A. Gray) C.L. Hitchc.	Solanaceae	Native	Zizka (1991)	*Lycium sandwicense* A. Gray		x
Macaranga spec.	Euphorbiaceae	Native	Flenley et al. (1991), Horrocks et al. (2013)		Only documented by pollen records, no species identified. Several endemic species in French Polynesia (pers. comm. Jean-Francois Butaud)	x
Metrosideros spec.	Myrtaceae	Native	Flenley et al. (1991), Butler and Flenly (2010)		Only documented by pollen records, no species identified. Butler and Flenley (2010) refer only to family Myrtaceae.	x
Metroxylon sagu Rottb.	Arecaceae	Doubtful	Bowdery (2015)		Only documented by phytoliths. Hypothetical species ("best match" of phytoliths with recent species).	
Metroxylon vitiense (H. Wendl.) Hook. f.	Arecaceae	Doubtful	Bowdery (2015)		Only documented by phytoliths. Hypothetical species ("best match" of phytoliths with recent species).	
Myrsine spec.	Primulaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Oxybasis glauca (L.) S. Fuentes, Uotila & Borsch	Amaranthaceae	Native	Zizka (1991)	*Chenopodium glaucum* L.		x

Paschalococos disperta J. Dransf.	Arecaceae	Endemic	Zizka (1991)		Extinct.	x
Paspalum forsterianum Flügge	Poaceae	Endemic	Zizka (1991)			x
Peperomia tetraphylla (G. Forst.) Hook. & Arn.	Piperaceae	Native	Skottsberg (1956)			x
Persicaria acuminata (Kunth) M. Gomez	Polygonaceae	Native	Zizka (1991)	*Polygonum acuminatum* Kunth		x
Pittosporum spec.	Pittosporaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Plantago spec.	Plantaginaceae	Native	Azizi and Flenley (2008), Cañellas-Bolta et al. (2013), Horrocks et al. (2013)		Family Plantaginaceae documented by pollen records before arrival of humans.	x
Portulaca oleracea L.	Portulacaceae	Native	Zizka (1991)			x
Potamogeton spec.	Potamogetonaceae	Native	Flenley et al. (1991), Horrocks et al. (2015)		Only genus documented by pollen records, no species identified.	x
Premna cf. *serratifolia* L.	Lamiaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Pritchardia vuylstekeana H. Wendl.	Arecaceae	Doubtful	Bowdery (2015)		Only documented by phytoliths. Hypothetical species (“best match” of phytoliths with recent species).	

Psychotria spec.	Rubiaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Psydrax cf. *odorata* (G. Forst.) A.C. Sm. & S.P. Darwin	Rubiaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Pycreus polystachyos (Rottb.) P. Beauv.	Cyperaceae	Native	Zizka (1991)	*Cyperus polystachyos* Rottb.		x
Rytidosperma paschale (Pilg.) C.M. Baeza	Poaceae	Endemic	Zizka (1991), Baeza (1991)	*Danthonia paschalis* Pilg.		x
Samolus repens Pers.	Primulaceae	Native	Zizka (1991)			x
Santalumc spec.	Santalaceae	Doubtful	Forster (1778–1780), Skottsberg (1956)		Based on G. Forsters report of a carved wooden hand. See discussion in Skottsberg (1956). Regarded doubtful.	
Sapindus saponaria L.	Sapindaceae	Native	Butler and Flenley (2010)		*Sapindus saponaria* is occurring on the island, possibly a Polynesian introduction (Zizka 1991).	x
Schenkia spicata (L.) G. Mans.	Gentianaceae	Native	Zizka (1991)	*Centaurium spicatum* (L.) Fritsch		x
Schoenoplectus californicus (C.A. Mey.) J. Soják	Cyperaceae	Native	Zizka (1991)	*Scirpus californicus* (C.A. Mey.) Steudel		x
Sesuvium portulacastrum (L.) L.	Aizoaceae	Doubtful	Hemsley (1885)		One single record in literature, no herbarium specimens available, doubtful (Zizka 1991).	

Solanum opacum A. Braun & C.D. Bouché	Solanaceae	Native	Zizka (1991)	*Solanum forsteri* Seem.		x
Sophora toromiro Skottsb.	Fabaceae	Endemic	Zizka (1991)		Extinct in the wild.	x
Sporobolus africanus (Poir.) Robyns & Tournay	Poaceae	Native	Zizka (1991)			x
Tetragonia tetragonoides (Pall.) Kuntze	Aizoaceae	Native	Zizka (1991)			x
Thespesia populnea (L.) Sol. ex Correa	Malvaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	
Trema spec.	Ulmaceae	Native	Flenley et al. (1991), Butler and Flenley (2010)		Only genus documented by pollen records, no species identified.	x
Triumfetta semitriloba Jacq.	Malvaceae	Native	Zizka (1991)			x
Typha spec.	Typhaceae	Native	Flenley et al. (1991)		Only genus documented by pollen records, no species identified.	x
Verbena litoralis Kunth	Verbenaceae	Native	Cañellas-Bolta et al. (2013)		Regarded introduced by Zizka (1991). Cañellas-Bolta et al. (2013) document pollen as early as app. 3000 BP.	x
Xylosma cf. *suaveolens* (J.R. Forst. & G. Forst.) G. Forst.	Salicaceae	Doubtful	Orliac (1998)		Based on identification of charcoal, ca. 300–600 years old. Possibly Polynesian introduction or driftwood.	

Clubmosses (Lycopodiopsida, Lycopodiales)						
Huperzia spec.	Lycopodiaceae	Native	Rull et al. (2015)		Only documented by spores.	x
Lycopodium spec.	Lycopodiaceae	Native	Butler and Flenley (2010), Horrocks et al. (2015)		Only documented by spores.	x
Fern allies (Polypodiopsida, Ophioglossidae)						
Ophioglossum lusitanicum L. subsp. *coriaceum* (A. Cunn.) R.T. Clausen	Ophioglossaceae	Native	Meyer (2013)	*Ophioglossum coriaceum* A. Cunn.	Possibly *O. nudicaule* L. f. (pers. comm. Jean-Francois Butaud).	x
Ophioglossum reticulatum L.	Ophioglossaceae	Native	Meyer (2013)			x
Psilotum nudum (L.) P. Beauv.	Psilotaceae	Native	Meyer (2013)			x
Ferns (Polypodiopsida, Polypodiidae)						
Asplenium polyodon G. Forst. var. *squamulosum* (C. Chr.) R.A. Rodr.	Aspleniaceae	Endemic	Meyer (2013)	*Asplenium praemorsum* Sw., *Asplenium adiantoides* Lam. var. *squamulosum* Chr. & Skottsb., *Asplenium indusiatum* Copeland	Endemic variety. According to Base de données Nadeaud de l'Herbier de la Polynésie française, the correct name is *Asplenium indusiatum* Copel. (see URL: http://nadeaud.ilm.pf/details-referentiel/20815).	x
Asplenium obtusatum G. Forst. var. *obtusatum*	Aspleniaceae	Native	Meyer (2013)		According to Brownsey and Perrie (2016) the correct name is *Asplenium decurrens* Willd.	x
Cyathea spec.	Cyatheaceae	Native	Azizi and Flenley (2008)		Only documented by spores.	x

Cyclosorus interruptus (Willd.) H. Ito	Thelypteridaceae	Native	Meyer (2013)	*Thelypteris interrupta* (Willd.) K. Iwats.		x
Davallia solida (Forst.) Sw.	Davalliaceae	Native	Meyer (2013)			x
Diplazium fuenzalidae Espin.	Athyriaceae	Endemic	Meyer (2013)			x
Doodia paschalis C. Chr.	Blechnaceae	Endemic	Meyer (2013)	*Blechnum paschale* (C. Chr.) Christenh.		x
Dryopteris karwinskyana (Mett.) Kuntze	Dryopteridaceae	Native	Meyer (2013)	*Thelypteris espinosae* (Hicken) Rodr.		x
Elaphoglossum skottsbergii Krajina	Dryopteridaceae	Endemic	Meyer (2013)			x
Haplopteris ensiformis (Sw.) E.H. Crane	Pteridaceae	Native	Meyer (2013)	*Vittaria elongata* Sw.		x
Hymenophyllum spec. Sm.	Hymenophyllaceae	Native	Butler and Flenley (2010)		Only documented by spores.	x
Microlepia strigosa (Thunb.) C. Presl	Dennstaedtiaceae	Native	Meyer (2013)			x
Phymatosorus parksii (Copel.) Brownlie	Polypodiaceae	Native	Meyer (2013)	*Microsorum parksii* (Copel.) Copel.		x

Pneumatopteris costata (Brackenr.) Holttum var. *hispida* Holttum	Thelypteridaceae	Native	Meyer (2013)	*Thelypteris luzonica* (Christ) C.F. Reed		x
Polystichum fuentesii Espin.	Dryopteridaceae	Endemic	Meyer (2013)			x
Pteris spec.	Pteridaceae	Native	Butler and Flenley (2010)		Only documented by spores.	x
Mosses (Bryophyta)						
Aongstroemia hookeri Müll. Hal.	Dicranaceae	Native	Ireland and Bellolio (2002)	*Dicranella hookeri* (Müll. Hal.) Cardot		x
Blindia magellanica W.P. Schimper	Seligeriaceae	Native	Ireland and Bellolio (2002)			x
Brachymenium indicum Bosch & Sande Lacoste	Bryaceae	Native	Ireland and Bellolio (2002)			x
Bryum argenteum Hedw.	Bryaceae	Native	Ireland and Bellolio (2002)			x
Bryum argenteum Hedw. var. *lanatum* (P. Beauv.) Hampe	Bryaceae	Native	Ireland and Bellolio (2002)			x
Campylopus clavatus Wilson	Dicranaceae	Native	Ireland and Bellolio (2002)			x

Campylopus introflexus (Hedw.) Brid.	Dicranaceae	Native	Ireland and Bellolio (2002)			x
Campylopus vesticaulis Mitten	Dicranaceae	Native	Ireland and Bellolio (2002)			x
Campylopus spec.	Dicranaceae	Native	Ireland and Bellolio (2002)			x
Ceratodon purpureus (Hedw.) Brid.	Ditrichiaceae	Native	Ireland and Bellolio (2002)			x
Chenia leptophylla Zander	Pottiaceae	Native	Ireland and Bellolio (2002)			x
Dicranella hawaiica Brotherus	Dicranaceae	Native	Ireland and Bellolio (2002)			x
Dicranum campylophyllum Taylor	Dicranaceae	Native	Ireland and Bellolio (2002)	*Dicranella campylophylla* (Taylor) A. Jaeger		x
Ditrichium difficile Fleischer	Ditrichiaceae	Native	Ireland and Bellolio (2002)			x
Fabronia jamesonii Taylor	Fabroniaceae	Native	Ireland and Bellolio (2002)			x
Fissidens pascuanus Brotherus	Fissidentaceae	Endemic	Ireland and Bellolio (2002)			x
Fissidens pellucidus Hornschuch	Fissidentaceae	Native	Ireland and Bellolio (2002)			x
Isopterygium albescens Jaeger	Hypnaceae	Native	Ireland and Bellolio (2002)			x

Leptobryum pyriforme Wilson	Bryaceae	Native	Ireland and Bellolio (2002)			x
Macromitrium spec.	Orthotrichaceae	Native	Ireland and Bellolio (2002)			x
Papillaria crocea Jaeger	Meteoriaceae	native	Ireland and Bellolio (2002)			x
Philonotis hastata Wijk & Margadant	Bartramiaceae	Native	Ireland and Bellolio (2002)			x
Pohlia spec.	Bryaceae	Native	Ireland and Bellolio (2002)			x
Ptychomitrium subcylindricum Theriot	Ptychomitriaceae	Endemic	Ireland and Bellolio (2002)			x
Pyrrhobryum spiniforme Mitten	Rhizogoniaceae	Native	Ireland and Bellolio (2002)			x
Racopilum cuspidigerum Angström	Racopilaceae	Native	Ireland and Bellolio (2002)			x
Sematophyllum aberrans E.B. Bartram	Sematophyllaceae	Native	Ireland and Bellolio (2002)			x
Sematophyllum brachycladulum Brotherus	Sematophyllaceae	Native	Ireland and Bellolio (2002)			x

Tortella humilis Jennings	Pottiaceae	Native	Ireland and Bellolio (2002)			x
Trematodon pascuanus Theriot	Bruchiaceae	Endemic	Ireland and Bellolio (2002)			x
Trichostomum brachydontium Bruch	Pottiaceae	Native	Ireland and Bellolio (2002)			x
Weissia controversa Hedw.	Pottiaceae	Native	Ireland and Bellolio (2002)			x
Weissia spec.	Pottiaceae	Native	Ireland and Bellolio (2002)			x
Liverworts (Marchantiophyta)						
Acrobolbus knightii (Mitt.) Briscoe	Acrobolbaceae	Native	Grolle (2002), Ireland and Bellolio (2002)	*Marsupidium knightii* Mitt.		x
Cephaloziella spec.	Cephaloziellaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Dumortiera hirsuta (Sw.) Nees	Dumortieraceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Frullania ericoides Raddi	Frullaniaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Jackiella javanica Schiffn.	Jackiellaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x

Lejeunea flava (Sw.) Nees	Lejeuneaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Lejeunea minutiloba A. Evans	Lejeuneaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Lophocolea aberrans Lindenb. & Gottsche	Lophocoleaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Marchantia berteroana Lehm. & Lindenb.	Marchantiaceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Myriocoleopsis minutissima (Sm.) R.L. Zhu, Y. Yu & Pocs subsp. *myriocarpa* (Nees & Mont.) R.L. Zhu, Y. Yu & Pocs	Lejeuneaceae	Native	Grolle (2002), Ireland and Bellolio (2002)	*Cololejeunea minutissima* (Sm.) Schiffn.		x
Riccardia tenerrima (Steph.) A. Evans	Aneuraceae	Native	Grolle (2002), Ireland and Bellolio (2002)			x
Hornworts (Anthocerotophyta)						
Gen. spec.	Family	Native	Grolle (2002)			

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Chapter 15
Palms for the Archaeologist

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1 Introduction

If your historical/cultural/linguistic past harks back to temperate Europe or colonial North America, and you speak English, when you think of *trees* you might envision apple (*Malus*), ash (*Fraxinus*), beech (*Fagus*), birch (*Betula*), cedar (*Juniperus*), chestnut (*Aesculus*), elm (*Ulmus*), hemlock (*Tsuga*), maple (*Acer*), oak (*Quercus*), olive (*Olea*), or pine (*Pinus*). Trees give shade, sugar, fruit, and nuts; trees underpin our material realm, providing studs, shingles, clapboards, rafters, keels, and masts. Trees serve as rich symbols, as metaphors for knowledge and life (the two trees of Genesis), death and afterlife (Calvary, Revelation 22), and a host of relationships (family trees, phylogenetic trees, cladograms). Nations often choose trees for symbolic representation: in Wikipedia's Listing of National Trees (accessed 2020); 17 out of 86 in the sample are members of the genus *Quercus*, the most named genus, associated with mainly European nations, English speaking or not. Four countries designate *Pinus*. *Pinus* is classified as neither monocot nor dicot sensu *lato*, as is also the case for cedar and hemlock, but rather as gymnosperms, aka Acrogymnospermae. The USA is one of the 17 nations that goes with oak; Canada opts for maple. Six countries (Cambodia, Columbia, Cuba, Haiti, Maldives, Saudi

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_15

Arabia) picked palms—monocots—but by far the international leaning is toward dicot trees.

Palms also figure symbolically, not only in ancient Mesopotamian religions, but also in the Near East and in the Mediterranean, particularly making reference to one of the arguably oldest cultivated plants, the date palm (*Phoenix dactylifera*). Worldwide, palm symbolism plays important roles in the Bible, in Christianity's rituals of Palm Sunday and Holy Week, and in Judaism's prayers of the feast of Sukkot. Symbolic referents include peace, victory, and eternal life. Many of these symbolic referents are to leaves, as in the palm crosses of Palm Sunday. In North America above the normal ecological range of palms, we often have observed two types of palms—one of artificial materials such as plastic, and the other of transplanted palms that might only survive the summer season, especially when planted in temperate regions. Both types of palms decorate pleasure destinations like casinos, water parks, miniature golf courses, and the ubiquitous Tiki bars and restaurants. The symbolic intent: to create the aura of a tropical paradise, often associated with but not solely coastal areas. Hundreds of palm individuals grown in nurseries in the southern USA travel by the truck load to more northern destinations every spring. We know of one Chincoteague Island, Virginia (USA), miniature golf course owner who successfully beats the winter kill by wrapping his palms in clear plastic (and therefore protecting the only apical meristem characterizing palms). Another miniature golf course just across the street displays plastic palms. Not far away, a restaurant on Chincoteague Bay buys replacement palms every year for its outdoor dining area. The latter may reflect how inexpensive palms have become in nursery centers in the past two decades.

We would suggest that in the temperate European and North American subconsciousness, the culturally assigned attributes of trees in the dicot and the gymnosperm genera mentioned above include endurance, solidity, strength, durability, connectedness, and transcendence. Part of the conceptualization also embraces such basic attributes as bark, branching, grain, tree rings, and roots (as in root metaphor—Google "root metaphor" and see what you get!). If you think of trees in this folk taxonomic way, and then you project that schema onto palms, you may inadvertently make some dissonant assumptions about palms. If your cultural image of "treeness" morphs to palms, you might expect palms to branch above (which occurs naturally only in the palm genus Hyphaene) and below (roots) ground, to be solid through and through, to float, to build watercraft, and perhaps to exhibit inbuilt age.

2 Monocot/Dicot sensu *lato* (Including Early Angiosperms and Eudicots)/Gymnosperm

We begin with a comparison of monocot and dicot sensu *lato* characteristics, and then will add commentary on conifers, classified among gymnosperms. Monocots and dicots sensu *lato* are Angiosperms (Angiospermae) or flowering plants. Cotyledon (as in cot- or -cot) refers to the first embryonic leaf or the seed leaf in plants.

Dicots sensu *lato* (Class *Magnoliopsida*) have two cotyledons in the embryo; the resulting plants are labeled dicotyledons. Characteristics of dicots sensu *lato* include pollen with three or four furrows, multiples of four or five flower parts, reticulated leaf veins, vascular bundles arranged in a ring, and roots that emerge from the radicle in the lower part of the embryo, and the phenomenon of secondary growth in stem diameter, with cambium present (Monocots versus dicots 2020). Examples include trees mentioned above such as oaks, maples, beech, and birch (excepting cedar, hemlock, pine), and also other plants like roses, cacti, lettuce, tomatoes, and legumes like peas and beans.

Monocots have a usually single cotyledon in the embryo, single pore or furrow, multiples of three flower parts, parallel rather than reticulate or branched leaf veins, vascular bundles (issued from a primary meristem called procambium) dispersed in the stem rather than located in a ring, adventitious roots emerging from the basal regions of the stem, and the lack of secondary growth, with cambium absent. Examples include palms, wheat, and also corn (maize), sugar cane, bamboo, grass, tulips, and onions. For a useful summary of differences between Monocotyledonae and Dicotyledonae (in modern classifications further split into early divergent angiosperms and eudicots or true dicots), see Tomlinson (1990: 133-135).

Conifers, in the USDA classification system (USDA plants database, n.d.), members of the division Pinophyta, aka Coniferophyta or Coniferae, include cedars (Genus *Juniperus*), pines (Genus *Pinus*), and hemlocks (Genus *Tsuga*) (all three exemplified here are of the family Pinaceae). These share many general "treeness" characteristics with dicot trees such as tree rings, grain, branching limbs and roots, and compact, solid interiors. Unlike angiosperms, double fertilization (producing the embryo and the endosperm) lacks in this group. As gymnosperms, the seeds are described as naked and in the Pinaceae are produced in cones. The Pinaceae are monecious (male and female cones present in the same individual), are resinous, and have needle-like leaves. In material culture terms, conifers like cedars, pines, and hemlocks can be used for timber just as with dicot trees—including masts, beams, flooring, clapboards, studs, and shingles.

We will briefly note here in this classification section that preferred trees for Polynesian canoes such as *Alphitonia zizyphoides*, *Elaeocarpus raratongensis*, and *Acacia koa* are dicots in the USDA classifications system.

3 Structural Differences

What are some of the structural differences involved, trees of the dicots sensu *lato* and gymnosperms persuasion versus monocots? From this point on, we will use the term "DG" trees to refer to the dicots sensu *lato* and gymnosperm tree contingent and "AP" trees to refer to palms in the order Arecales and the family Arecaceae or Palmae (187 genera, 2600 species), as in the genera *Cocos*, *Jubaea, Juania*, *Roystonea*, and *Syagrus*.

DG trees grow by adding rings of xylem (usually dark colored, in which water and nutrients are transported up; xylem position is inner in respect to phloem) and phloem (usually light colored, and which conduct sugars and metabolites down or up; phloem position is outer in respect to xylem) which are separated by cambium. The cambium generates the xylem and phloem, and is shielded on the outside from the elements by cortex or outer bark. As the DG tree develops, newly generated xylem and phloem rings surround the former rings with the old rings becoming sapwood—or what might be called dead carbon. In temperate regions, DG trees usually add a xylem/phloem ring set each year. Typically, but not without exception, a faster growing, lighter colored part of the ring develops in the early season (early wood) followed by a darker colored part of the total ring (latewood). Complications: false bands may be generated, and in tropical regions, multiple rings sets may be generated within a year.

But what we wish to emphasize here is that temperate or tropical, the sapwood in DG trees is relatively hard, compact, and consistent from periphery to center. Rings are visible in cross section in the stem, and vertically, are perceptible as grain when split or sawn. As the DG tree grows, the tree expands in width and height by adding rings issued from secondary growth. Because of this phenomenon of internal consistency, a DG tree can make a serviceable beam, stud, clapboard, or shingle for a building, or a gunnel, lapstrake plank, keel, or mast for a vessel.

AP trees differ substantially in their structure from DG trees. Here we will focus mainly on the stem (vs. the DG trunk), but major differences occur also, for example, in the adventitious root system, in leaf development from the apical meristem, and in the general lack of branching (with the exception of the genus *Hyphaene*, or originated by injury of the stem). For a convenient summary of differences, see Hodel (2009). For extensive information, see Tomlinson's volume *Structural biology of palms* (1990).

In cross section, AP trees possess an outer cortex surrounding a central cylinder. Hodel describes it this way:

> In cross section, the palm stem has two distinct regions, the cortex and central cylinder (Fig. 15.3) (Tomlinson 1990). The cortex, a very narrow band on the outside of the stem, has a thin outer covering or skin composed primarily of thick-walled, sclerified (hardened) cells, which is sometimes referred to as pseudobark, although it has no relation to bark of dicotyledonous and coniferous trees. Relatively unspecialized parenchyma cells, which may become larger, more numerous, and lignified (woody) with age, compose most of the remainder of the cortex. [Hodel 2009: 678]

The pseudo bark and cortex represent a relatively small proportion of the total stem diameter, but the cortex can be quite hard and also brittle. Unlike DG trees, there is no peripheral cambium supporting secondary growth as most of the vascular tissue will develop from a primary meristem procambium and be characterized by its limited growth. What is really in stark contrast to DG trees is that the central cylinder, which occupies most of the area of the palm stem, is composed almost entirely of vascular bundles—not tree rings. The vascular bundles contain the phloem and xylem and each of these vascular bundles is partially or entirely enclosed by "a strong, hard, fibrous sheath" that provides efficient resistance to the palm stem. Much of the support for the palm stem derives from these bundles (Hodel 2009: 678). The vascular bundles are

> embedded in a mostly homogeneous, light colored ground tissue made up of largely unspecialized parenchyma (Dransfield et al. 2008; Tomlinson 1990). The parenchyma cells which store water and carbohydrates such as starch, tend to become woody with age, especially those toward the outer part of the central cylinder, while those toward the center of the central cylinder are mostly spongy and unlignified (Tomlinson 2006). [Hodel 2009: 678]

The proportion of cortex to central cylinder is quite small. William Liller observed *Jubaea chilensis* in Las Campanas, a Chilean National Park, and inspected two dead palms. Gurley and Liller report schematic densities ranging from 210 to 540 kg/m^3 (1997:83) and the thickness of "the tough outer bark, or pericarp which averaged 5 millimeters in thickness and with a density of from 1300 to 1640 kg/m^3." This density they state is similar to that of bone or ivory and is "denser even than *lignum vitae* or ironwood" (Gurley and Liller 1997: 84). In their Figure 3, "Schematic density distribution in a mature *Jubaea chilensis*" they illustrate a transition zone between the "pericarp" and the "fibrous" interior of 20 millimeters. Flenley and Bahn repeat the 5 millimeter figure for the "outer bark" (2002: 124), accompanied by ill. 34, a photograph, "A cross-section of a Chilean wine palm, showing the thin, hard rind and fibrous interior" (they cite Gurley and Liller 1997). Note that the term pericarp usually and technically relates to the fruit and corresponds to the outer layers of the fruit wall, in turn divided into the three regions endocarp, mesocarp, and exocarp, but in Gurley and Liller, it refers unconventionally to the outer bark. Later we will return to Gurley and Liller (1997) and Flenley and Bahn (2002) in respect to the possibility of using palms for rollers under the *moai*.

Whereas DG trees have a continuously hard, solid, and dry interiors, AP trees like *Cocos nucifera* and *Jubaea chilensis* (and likely the extinct *Paschalococos disperta*) possess relatively soft interiors compared to the outer cortex. First, we would call attention to the AP cortex which represents quite a small proportion of the total diameter. In Figs. 15.1 and 15.2, we show cross sections of fresh cut coconut palm and royal palm stems, respectively, kindly donated to us by a road crew on Molokai. A knife marks where it is very easy to insert the blade as the denser cortex is approached. There is no apparent tissue border here; rather, it is a simply a matter of increasing density of the vascular bundles as the outer edge is approached. As Tomlinson (1990:126) writes about palms in general, "The boundary between cortex and central cylinder is represented only by an abrupt transition in texture of ground tissue and density of vascular bundles; there is no limiting endodermis or other specialized boundary layers."

The tape measure in Fig. 15.1 of the coconut palm stem shows about 0.5 inches (ca. 13 mm) thickness of cortex in a stem diameter of about 8 inches (ca. 20 cm). The cortex would thus represent about 12–13% of the radius or the diameter. The remaining ca. 87–88% of the central cylinder is much softer and less tightly packed. In Fig. 15.2 of the royal palm, the cortex measures from about 0.75 to 1 inch (ca. 19 mm to 25 mm) in width, in a diameter of about 13.5″ (ca. 34 cm), representing

Fig. 15.1 Stem segment of coconut palm, Molokai (Hawaii). The scale is inches, 2.54 cm/inch, The knife marks the easy insertion point, at ca ½” or about 10 mm, between the cortex and the central cylinder. Photograph by authors, 2012

Fig. 15.2 Stem segment of royal palm, Molokai (Hawaii), showing loose vascular bundles. Photograph by authors, 2012

about 14% of the radius or diameter. Compare these proportions to those of Gurley and Liller's *Jubaea chilensis* stem transition zone (roughly equivalent to where the knife blade is located in Figs. 15.1 and 15.2) of 40 mm (20 × 2) out of 1 meter stem diameter: about 4%. The illustration of a complete cross section of an actual 0.6 m *Jubaea chilensis* stem, shown in Guzman et al. Fig. 3a (2017:188) we suggest, shows proportions of cortex to central cylinder similar to our Figs. 15.1 and 15.2 coconut and royal palm examples.

When freshly cut, the palm stem central cylinder is rich with moisture and carbohydrate like starch and sugars—in the fundamental parenchyma, in the vascular bundles—perhaps especially in the case of the wine palm, *Jubaea chilensis* (see output values later in this chapter). In our 2012 Molokai experiments, when son-in-law Jon Smith and we put newly cut royal and coconut palm stem segments in a barrel full of freshwater, we were surprised when the segments sank. The same test applied to dry segments of royal and coconut palm: the segments floated but initially with only about 1/8 of their diameter above the surface; over the next few days, the segments absorbed water and were barely breaching the surface.

In 2009, we may have experienced a premonition of this phenomenon: when snorkeling in a restored Molokai fish pond, we observed palm logs underwater. We wondered at the time, why were they sunken? In 2012, we conducted a survey of several miles of Molokai's west and south shores. Although we saw lots of palms by the shore, we saw no palm driftwood except immediately in front of two eco-camps where they had been cut down but had not traveled very far. The lesson we learned: those vascular bundles which comprise such a massive volume of the palm stem central cylinder can retain or lose massive volumes of moisture; we also suspect that the fundamental parenchyma is able to retain substantial amounts of water. Unlike the hard and dry interiors of DG trees, the central cylinders of palms are like thousands of liquid-filled pipes while the palms are alive. When newly cut and fresh, the palms we tested had a specific gravity greater than fresh or ocean water.

An index of how much moisture a palm stem can harbor is in the amount of sap. According to Bork and Mieth, a medium-sized trunk of *Jubaea*, about 10 m in height and about 0.5 m in diameter could have "nearly 2 m^3 of trunk wood." Bork and Mieth report possible volumes of sap from 300 to 400 liters (citing Darwin 2001; Rundel 2003–04; Grau 1998; and Orliac 2003) for the central region of Chile. For their purposes, Bork and Mieth estimate 50–150 liters (Bork and Mieth 2003: 120, 121). Delhon and Orliac repeat the approximately 400 liter volume in a subsequent publication (2007:97). Incidentally, the usual method reported for obtaining sap involves felling the palm rather than tapping it like in other African (*Borassus*, *Elaeis*, *Hyphaene*, *Raphia*) or Asian palms (*Arenga*), or in dicots sensu *lato*, such as the maple tree, removing the fronds, making a cut at the apical meristem, and capturing the drip. In other parts of the world, palms are repeatedly climbed to tap their inflorescences (*Arenga*, *Caryota*), which the palms can survive (Dalibard 2009). Felling was the means reported by Darwin (1845: Chapter XII, August 16th), who noted the palm would be felled up slope rather than down slope.

One cubic meter equals 1000 liters; if the high value of 400 liters derives from about 2m^{3,} of stem volume, that is about 20% of the stem volume. We recommend that you visit the link for Darwin (1845) for a fascinating description of his palm sap comments.

When dead and dried out, however, the vascular bundle tubes are as dry and flexible as broom straws. In Fig. 15.2, this condition is especially visible in a dry stem segment of royal palm. The vascular bundle tubes can easily be drawn out by hand like straws. With the blow of an axe, these palm stems, both in the royal and coconut segments, are surprisingly brittle and can be readily split in the vertical dimension. Notice the already existing cracks in the cortex in Fig. 15.2. Remarkably, once split open, we found that the vascular bundles in coconut and royal palms could be removed by hand, no tools needed, thus totally evacuating the central cylinder. Granted, coconut and royal palms are not *Jubaea chilensis*, but in Fig. 3a in Guzmán et al. (2017), the *Jubaea chilensis* cross section although larger in diameter appears similar in central cylinder vascular bundle arrangement and proportion. The fact that all three genera are phylogenetically related may suggest a common stem structure, particularly visible through the density and the arrangement of vascular bundles in the stem.

One implication of the moisture and nutrient-rich vascular bundles of the central cylinder includes the propensity for rapid decay. In a very short time, a downed palm (coconut we think) can look like the one shown in Fig. 15.3, at Anakena. Here, not only is the central cylinder in a state of advanced decay, but so is the cortex. Incidentally, it has observed the paucity of palm charcoal on Rapa Nui (Delhon and Orliac 2007: 99; Rull et al. 2010:58). Could it be palm's tendency to rot rapidly? On

Fig. 15.3 Rotting coconut palm at Anakena (Rapa Nui). Photograph by authors, 2010

arid western Molokai, following the suspension of irrigation at a golf course and at an eco-camp, we noted subsequent death and toppling of substantial palms followed by rapid decay; the time frame was two to three years. Indeed, a large majority of palms need high ground water, whereas only a limited number of palm genera (i.e., *Hyphaene*, *Medemia*, *Washingtonia*) are truly adapted to xeric conditions.

> As for the commonly asked question as to how the discoverers [of Rapa Nui] did not witness the traces of thousands of collapsed trunks that would have resulted from extermination we have found an answer in the fact that the author once revisited a palm orchard after a 60 period, where hundreds of cut palms once covered the ground. Surprisingly, there were no traces of them (Fig. 9). The putrefaction process that goes from inside out is the answer. The process starts in the fiber-vascular tissue and advances toward the bark (Grau 2005:32)

The trunks Grau mentions were massive *Jubaea chilensis* trunks about a meter in diameter, felled for their sap, in a palm forest where he camped as a youth all those years ago (Grau 1997: 124). Compare this outcome to long-dead (since ca. 1915), blight-killed American chestnut (*Castanea dentata*) trees one of us observed in the Quabbin Reservoir (central Massachusetts, USA) which were still being taken to sawmills to make barn timbers in the early 1970s. Similarly, Holmes (1981:17) cites foresters stating fifty to seventy years might be required for the decomposition of *koa*. In terms of archeological evidence, much of palm stem biomass, unless perhaps charred, would seem likely to be lost, excepting phytoliths.

4 Canoes? Rollers and Sledges? Lumber?

4.1 Canoes?

Because in the majority of AP trees, the central stem cylinder is composed of vascular bundles and is not solid and compact compared to DG trees, we suggest that the AP stem in general is not a good candidate for canoe keels, planks, or ribs. On the one hand, because the central cylinder vascular bundles can be very wet, rendering the total stem mass of greater specific gravity than water, the palm would not float if fresh. On the other hand, if the vascular bundles have become desiccated, then the risk is a sponge-like effect of water absorption, waterlogging the craft. If the mass of flexible vascular bundles is removed in the central region of the trunk, only the thin brittle cortex remains. This cortex would not be a suitable material for the keels of an ocean going double voyaging canoes, in part, because palm stem cortex could not be shaped or carved in the manner of DG trunks, as in the Hawaiian case (Jones 2007: 307, 2011: 86–87; Holmes 1981:8) where the keels were carved from solid logs and then plank sides were built up, or a large tree provided the entire hull. If the cortex is split longitudinally into planks for lapstrake (clinker built) or non-lapped (carvel-built) hull application, the challenge of dealing with the latitudinal curvature of the cortex planks presents itself. Constructing a canoe hull by sewing curved planks together in the manner of the Rapa Nui canoes observed by Europeans like Forster or de la Pérouse (see Flenley and Bahn 2002:37, Fig. 14, and Boersema 2015:17, Fig. 2.5) would be difficult. Over 20 years ago, Hunter-Anderson, in a long passage citing several sources and individuals, addressed disadvantages of palm for watercraft: "... it does not float well ... impossible to shape by adzing ... it sinks ... it swells and contracts with heat and cold ... (1998: 87-88). Whistler, in his book, Plants of the Canoe People: An Ethnobotanical Voyage through Polynesia comments "Undressed coconut timber is very strong and is used over much of Polynesia for posts and fences, in the framework of houses, and in many other ways, but is too heavy for planks or canoes" (2009: 74).

In the literature on world watercraft, Hunter-Anderson (1998 footnote 2, p. 97) found one example: "The only recorded case of palm wood being used for a canoe is on tiny Arorae, a low coral island in the and [sic] southern Gilberts (Kiribati) (Alexander 1902: 727). It is unknown if these canoes were used in the open ocean, or whether they were sailing canoes." We found another example (Ingersoll and Ingersoll 2016) of a type of canoe made by the Iquitos in the Peruvian Amazon of large palms (*Iriartea deltoid*ea), used to carry people and cargo downstream. The canoes were made quickly in a day or two (easy to hollow out!), took the downstream journey, and were then abandoned and not used for anything else such as fishing (Johnson and Mejía 1998: 208). They wrote "[p]alm canoes are temporary watercraft." They emphasized the vulnerability of the bow and stern, and noted that keeping the canoe in the water was needed to prevent drying and cracking. Our search through the Pacific watercraft literature in sources such as Hornell (1936) and Pâris (1843) for palm watercraft hull construction of palm yielded no examples; however, palm sennit lashings and coconut outrigger booms in the Tuamotus (Hornell 1936: 21, 59) and leaf use (Pâris 1843) were reported. Although one observer (1839) cited by Hornell had claimed that small Napuka canoes had been made by sewing coconut strips together, Hornell wrote "Wilkes is presumably in error regarding the timber employed. The coconut palm is never used in the Tuamotus for canoe planking" (1936: 55). The use of *Borassus aethiopum* to make canoes has been reported in West and South Africa (Acheampong 2014:11, Balami et al. 2016: 59, Salako et al. 2018:7, and Zongo et al. 2018: 69). Salako et al. illustrate a small canoe (Benin) in their Figure 3.

If not ocean going double canoes, could palm rafts have been fashioned on Rapa Nui? Certainly, sailing rafts are well documented in the Polynesian Pacific. Green (2001: 70) wrote in his article on sailing rafts: "Van Tilburg (1998:144) also makes a sensible suggestion that palm log rafts may have once been present in Easter Island before the Chilean oil palm of that island went extinct, leaving only *nga 'atu (totora)* reeds from which to manufacture a small float type raft-like vessel seen at contact." We predict that a palm raft would 1) not float if made of fresh palm stems and 2) would soon become waterlogged and unnavigable after launch if made of desiccated palm stems. Personally, we would not board such a raft.

4.2 Rollers and Sledges?

In the 2003 BBC documentary, *The Mystery of Easter Island*, the dialogue includes a line by David Steadman: “By the time palm trees got scarce on Easter Island everybody on the island knew they were in trouble. They loved palm trees, that’s what, how they made their good canoes, that’s how they rolled their statues. No palm trees equals we can’t move our statues anymore.” We have already reviewed canoe possibilities, but what about rollers and sledges for the *moai*? An extensive literature addresses a number of means of transporting the *moai*. How was it done is the question? Some of the transport models call for rollers—of palm.

We were skeptical, given the nature of palm cortex, that palm rollers could stand the stress and in that we were not alone. In a book review of Cotterell and Kamminga (1990), the review states that in reference to Mulloy’s proposed method, the authors offer that the “rollers would have been squashed” (Recent Publications, Rapa Nui Journal 4(1): 3). Similarly, MacIntyre (1999:36) states that “palms are not known as good canoe material, and I would not move *moai* on rollers (although palms might make adequate pylons at the quarry) . . . ”. Even John Dransfield (2010), noted palm expert, wrote “there is absolutely no evidence that trunks of the extinct palm were suitable and could have been used in that way” (as rollers for the *moai*). Van Tilburg writes:

> The trees of Rapa Nui’s prehistoric palm forest had a theoretical ability to attain smooth, cylindrical but uneven trunks more than 1 m in diameter. There is no evidence, however, that they ever attained this maximum size, nor is it clear that, if they did, their trunks would have been useful in statue transport. Rather, many “prints” of palm trunks embedded in hardened lava on the northwest coast of Rapa Nui (as documented by G. Figueroa) measure a less unwieldy 30 to 40 cm in diameter or less. [2009 np]

However, Van Tilburg (2009 np) conducted an experiment in a California construction yard with a pair of concrete Jersey road barriers set on a steel plate, barriers and plate combined yielding an approximate average statue weight, estimated at the time at about 12.5 m tons (Paro, the largest known *moai*, has an estimated weight of 75 m tons). These were placed on a pair of 7 m long 33 cm diameter palm trunks arranged in a V-shaped sledge form. Then the sledge was placed on rollers or sliders and then pulled by a fork lift truck. The “Results clearly demonstrate that palm wood is fully capable of bearing the requisite experimental load.” Not specified is distance of travel, but even if palm stems eventually collapsed, more could be supplied; also not specified is the genus and species of palm, which could be important, as for example, the characteristics of date palm trunks would not be the same as *Roystonea* trunks. The experiment was then successfully repeated with eucalyptus logs. Without experimental evidence like Van Tilburg’s, Gurley and Liller argued that mature palm trunks would make excellent rollers, “since the cylindrical form of the outer hardwood would support an estimated six tons before yielding, while the softer interior wood would provide a resilient inner spring” (1997:83). Previous studies in *moai* transport not by Van Tilburg reported *toromiro* for walkers, rollers, or sledges (Bahn and Flenley 1992:135, Love 2000:12). Grau thought that the palms would function as rollers for dorsally oriented *moai*, but over long distances *toromiro* trunks tied into a platform could be used to roll on top of palm trunks (1997:123). A reviewer of this chapter, an expert on Rapa Nui vegetation, disagreed with the suitability of *Paschalococos disperta* for rollers, given the stem structure of the palm deemed by many to be the most similar to it, *Jubaea chilensis*. The reviewer wrote "I have seen and touched transverse sections of *Jubaea chilensis*: the stem has an exceptional extensive very spongy part. I do not believe in the use of these stems as rollers for the moais. However, stem consistence of *Paschalococos disperta* might have been different."

Van Tilburg's experimental data argue that palms could function as rollers and sledges to move at least the average *moai*. Our next comment relates to palm supply and demand. If 19.7 million palms (Mieth and Bork 2018: 42) initially populated Rapa Nui and at least 887 documented *moai* were (Van Tilburg 2009) (additional *moai* may be located within ahu or covered by earth, etc.) created between about 1100 and 1680, an approximate 580 year time span, that translates into about 1.5 *moai* per year. Alternatively, if the palms were mostly gone within a 450 year time frame (Bork et al. 2019:153), that would be about 2 *moai* per year. Although Lee wrote of palms that

> [t]he land was cleared for crops, and the huge palm forests were cut down. The trunks of these trees likely were used as rollers to move the great statues, further decimating the groves of trees. By AD 1500, the population had spread over the island, the land was cleared (causing erosion and loss of productivity), and food resources were scarce. This is the Rapa Nui that we know the most about. [2004:113]

We suggest, conversely, that at about 1.5 to 2 *moai* per year, the specific draw on the palm population for *moai* transport rollers would be relatively minor, not approaching the level of decimation, whose historical meaning is to reduce by the tenth part.

4.3 Lumber?

This section addresses how palm sourced stems might be employed for lumber with a focus on the cautionary challenges of the material. A substantial commercial literature exists which deals with palm as a building material source. We will briefly examine one such source, Killmann and Fink (1996) which examines production of lumber from coconut palm stems. This exploration helps to suggest what might or might not have been feasible with *Paschalococos* stem material on Rapa Nui. When coconut palms reach about 60 years of age, their productivity declines—at this point the aging palms become a lumber potential. Killmann and Fink discuss production of such items as rafters, fence posts, utility poles, wall paneling, and furniture.

> *Timber exposed to weather must be chemically treated (for example, with pentachlorophenol) —this would include fence posts, utility poles, and siding (Section 2.1). Section 7.2 discusses application of wood preservatives
>
> * "Coconut palm wood has an initial moisture content ranging from 60% (high density) up to 230% (low density)." (Section 6, p. 75). To manage moisture, seasoning or drying is "essential" before processing
>
> *Killmann and Fink outline palm removal practices (stem, canopy, roots) to reduce the substantial disease risks from insects and fungi (Section 3) to the remaining palms. Leaving palms to rot in place is highly inadvisable. After milling or sawing, waste must be removed (Section 4.8). Among the risks are rhinoceros beetle (*Oryctes rhinoceros*) and palm weevil (*Rhynchophorus schach oliv*.) (see Ingersoll and Ingersoll 2018 for a review of palm disease and insect threats). Coconut wood, classified as "non-durable," should be dipped before storage to prevent fungi, mold, or insect attack (Section 7). Special stacking and storage procedures are outlined.
>
> *Cutting advice: special steels are recommended for sawing palms by whatever method, especially with Stellite tipped blades/teeth or tungsten-carbide (Section 4.7). Frequent re-sharpening is a must. Split boards are rough but can be used for shed rafters or trusses (Section 4.3.1) The sclerenchymatous vascular bundles often containing silica cause the dulling.
>
> *Because of inherent density variation between the cortex and the central cylinder, with much of the central cylinder too soft for lumber, sawing patterns typically square off the outer cortex, thus excluding a large proportion of the central cylinder (Section 4.1 and Figs. 19-22).
>
> * Many products made from palm wood, to achieve usable mass, require lamination, mortising and tenoning, or gluing (Sections 8.2.5, 8.6.8, 8.7). The fibrous vascular bundles can be used for particle board manufacture (Section 4.7).

Some of the observations drawn from Killmann and Fink about coconut above should be applicable in general to other related palms like *Jubaea*, and we would expect, *Paschalococos* (see below), for example, that the softer central cylinder material of coconut does not make for solid lumber, or that felled coconut stems tend to succumb to rot rapidly. If the extinct *Paschalococos* shares such capabilities and drawbacks, we might predict that it would not make for optimal architectural materials exposed to the weather, or for enduring canoes or canoe ladders.

5 Age, Dendrochronology, and ^{14}C

How long do palm trees live? Hunt and Lipo (2007:92) question Flenley and Bahn's lifespan claim for *Jubaea chilensis* of up to 2000 years as "unfounded" (Flenley and Bahn 2007a, b), but allow that an age of 400 years on Rapa Nui for *Jubaea* sp. or *Paschalococos disperta* might be possible. Hunt and Lipo (2007:92) quote Tomlinson's cautious position (2006:10): "[t]he age of the palm can only be determined accurately from knowledge of its seed planting date." Tomlinson provides an example, a *Jubaea chilensis* planted at Temperate House at the Royal Botanic Gardens, Kew, in 1843. This palm, 163 years old (presumably in 2006), can be observed in Tomlinson's Figure 1 (2006:6), where the caption states "It is said to be the largest and oldest single stemmed palm cultivated under glass outside its natural habitat." On the topic of palm lifespan, Tomlinson adds:

> Other examples, as summarized in Uhl and Dransfield (1987), are based on extrapolated values that range from 100 to 740 years. In trees traditionally thought to be thousands of years old, as in conifers [e.g. *Pinus longaeva* D.K. Bailey, *Sequoiadendron giganteum* (Lindl.) J. Bucholz], most of the tree's tissue is nonliving and phloem cells remain conducting for quite short periods. [Tomlinson 2006: 10]

This quote above by Tomlinson comparing palms to conifers brings us to a crucial difference: that conifers have growth rings and palms do not. Lacking growth rings, AP trees are not dateable by dendrochronology. There is likely some general age relationship between the series of leaf scars and age, but the whole stem would be needed, from root to apex, as well as an estimate of how many leaves (fronds) were on average generated and coexisting at any point in time to furnish the crown (leaf scars are visible in Figs. 15.1 and 15.3). Lack in Lack and Baker (2011:17) writes:

> Despite the lack of growth rings, it is possible to estimate the age of a palm by measuring the plastochron, the interval between the development of two subsequent leaves. By multiplying the plastochron with the sum of the number of leaf scars on the trunk plus the number of leaves in the crown, at least a rough age estimation can be obtained. With a measured age of 720 years, the Australian *Livistona eastonii* is one of the palm Methuselahs.

Note that the term "annular rings" has been applied to palms (Jones 1995: 23), but the above quote should make clear the differences between AP and DG trees' annular rings and tree rings, respectively. In reference to the above quote, we would emphasize the "rough age estimate" point, that due to variation in wet or dry years, the yearly production of leaves would vary, and that the counts would relate to *living* leaves in the crown (see quote above).

If the whole AP tree is needed for a rough age estimate, very few opportunities for dating will occur in archaeological contexts, which brings us to ^{14}C dating. Because DG trees contain massive volumes of nonliving material which can vary greatly in age of carbon deposition, with progressively older material moving toward the center from the bark, and downward in the trunk from the top. Where in the DG tree a radiocarbon sample comes from is highly relevant in regard to what besides the wood or charcoal sample is targeted to be dated by association. The phenomenon of inbuilt age presents serious challenges to developing chronologies, often leading analysts to the revision of prior technologies by seeking sample sources such as leaves, flowers, twigs, or seeds which avoid high inbuilt age problems and sidelining wood samples (see Wilmhurst et al. 2013).

The concept of inbuilt age has been applied to palms, as Hunt and Lipo (2007:89) write in reference to a palm wood charcoal date reported by Orliac and Orliac (2005:31): "However, dating palm wood is certainly problematic given its high-inbuilt age (Taylor and Higham 1998)." But in the source cited, Taylor and Higham do not actually seem to argue for high inbuilt age in palms (here the date palm, *Phoenix dactylifera* L.) but mention that "Zeuner considered the question of 'inbuilt' age." F. E. Zeuner (1960) did make an estimated age adjustment based on the sample's characteristics:

> Zeuner noted that palms show no annual growth increments (tree rings). The full thickness is formed first and then the tree grows upwards. For the tree to be high enough to be useful for ceiling rafters, it would have had to have been between 15 and 85 years old. [Taylor and Higham 1998:90]

This mention of lack of growth rings by Zeuner we wish to pursue here, because it may relate to the way inbuilt age and radiocarbon dating applies to palms. To further illustrate the relevance of palm structure, we supply some quotes from Tomlinson's *The Uniqueness of Palms*. He writes: "In contrast to the conducting elements of dicotyledons, however, palm vascular elements retain their conductive ability throughout the total life span of the tree" (Tomlinson 2006: 10), and

> The hydrosystem is massive in terms of water storage capacity, both in parenchyma and axial metaxylem, which remains permanently functional (Holbrook and Sinclair, 1992). [Tomlinson 2006: 9]
>
> Within the palm stems, both the sheathing fibres of the vascular bundles and the parenchyma cells of the ground tissue retain metabolic activity seemingly throughout the life of the palm (Figs. 2–10, 11–19). This is exhibited in continuous cell changes throughout the palm stem, those cells at the base of the trunk being oldest. This leads to a distinctive secondary diffuse thickening that is measurable (Schoute 1912). Metabolic activity is demonstrated structurally in several different ways. [Tomlinson 2006: 10]
>
> Perhaps the most distinctive property of palm stems is the ability of mature differentiated stem cells to retain their viability for centuries. [Tomlinson 2006: 13]

To the comments above, we would add Tomlinson's descriptions of the operation and schematics of the vascular system of palms (1990: 141–156). To see in detail how the vascular system connects to the leaf traces, see Tomlinson's section "Vascular system of *Rhapis*" and especially Fig. 6.12 (1990: 141–156) published in his comprehensive manual *The Structural Biology of Palms*. *Rhapis* is a genus of palms thought to be an appropriate model for palm vascular systems. Notable in all palms is the vascular continuity throughout the stem. In general how this works according to the "principle of borrowed bundles" is that "an axial bundle diverges from an outgoing leaf trace" (1990:155); as the palm grows, later that bundle continues upward through a series of leaf traces to the periphery, and heads toward the interior of the stem. Although lower leaves are lost and new ones are formed in the crown, the vascular system in a major way remains intact through the stem. An interesting phenomenon occurs of a spiraling effect of the rising vascular bundles in palms, resulting in the offset of each successive leaf placement, possibly positioning fronds for optimum exposure to light.

Several hypotheses can be framed in regard to how these palm characteristics might act to reduce or increase the inbuilt age effect: 1) water storage in a permanently functional system might promote new carbon exchange and reduce the inbuilt age effect, 2) lifelong metabolic activity in the stem might introduce new carbon in new or replacement cells and reduce the inbuilt age effect, 3) continued possible connection to the peripheral cortex by former leaf traces even after leaves are lost might introduce new carbon metabolically or by exchange and reduce the inbuilt age effect, 4) that the central cylinder is not composed of predominantly dead and isolated matter as in DG trees might reduce the extent of inbuilt age, 5) that old carbon is systematically maintained, increasing inbuilt age effect, and 6) that once carbon is placed, and the vascular bundles become progressively lignified, no new carbon is introduced, increasing the inbuilt age effect. The resolution of this question would seem to call for experimentation, in which ^{14}C sampling takes place at intervals along the full extent of the stem cortex, and at different depths within the central cylinder, of a recently dead palm. In short, how do ^{14}C dates vary with location within the palm stem?

6 Classical Taxonomy/Genomics

The palm we would really like to know about is the extinct palm of Rapa Nui referred to in the literature as *Paschalococos disperta* (see Zizka 1991:64–65 for Dransfield’s description), but in some cases also attributed to the modern taxon *Jubaea chilensis*. Both *Jubaea chilensis* and *Juania australis* (Dransfield et al. 1984; Hunter-Anderson 1998: 92) have been seen as potential predecessors of the large Rapa Nui palm. Possible evidence on Rapa Nui for the large palm includes charcoal, pollen, phytoliths, stem casts, root cylinders, and nuts. To complicate matters, there are other possible palms, also extinct, as reported by Gossen’s analyses of pollen and phytoliths in cores (2011): “The discovery in this research with the most impact was the loss of not only one palm species but of at least four palm types” (2011: 58). Gossen describes four types, the one closest to *Jubaea* designated as Type 1. Type 2a is a rounded pollen, Type 3 is smaller than *Jubaea*, and Type 4 is “a distinct pointed-end pollen” (2011:159). While nearest living genera and species are not proposed for the four types (they are possibly extinct), Gossen does state that “[n]one of these are *Cocos nucifera*. In Appendix A, Gossen furnishes numerous high definition color photomicrographs from a wide range of radiocarbon dated organic micro-remains from the sediments of the KA03 core of the crater lake Rano Kao. The remains include starch, rhizomes, charcoal, phytoliths, and pollen from many life forms. Photomicrographs of Types 1–4 may be viewed in Gossen (2011): 413, 415, 416, and on other pages in Appendices and A and D. Delhon and Orliac (2007) and Rull (2019) also mention the possibility of more than one palm species on Rapa Nui.

Next we would like to review the interrelatedness of the Cocoeae, in which both *Jubaea* and *Paschalococos* are included. To illustrate potential close structural stem characteristics, we will use Dransfield et al. (2008), which is a systematic updating of Dransfield and Uhl (1986), and a brief update to Dransfield et al. (2008) in Baker and Dransfield (2016).

In some classical taxonomical systems, the order Arecales is followed by the family Arecaceae, the subfamily Arecoideae, the tribe Cocoseae, and then the subtribe Attaleinae. In the subtribe Attaleinae, Baker and Dransfiled (2016:212) show 10 genera, which include *Beccariophoenix*, *Jubaeopsis*, *Voanioala*, *Allagoptera*, *Attalea*, *Butia*, *Cocos*, *Jubaea*, *Syagrus* and *Parajubaea*. Some of these may have been successfully crossed with *Jubaea* (see below).

While on the topic of classification, we will mention some of the other palms noted in this chapter. *Juania australis*, a palm formerly considered as a possible source or relative of the Rapa Nui palm, or as a species at one time on Rapa Nui is classified as subfamily Ceroxyloideae, tribe Ceroxyleae, genus *Juania* (Baker and Dransfield 2016:211). A study by Delhon and Orliac (2007: 107), however, concluded that the

> results of the morphometrical analysis show that, in most cases, fossil phytolith assemblages from Easter Island are close to those produced in the trunks of *Jubaea chilensis*. Thus, it seems that *Paschaloccocos disperta's*[sic] trunks are responsible for most of the phytoliths preserved in the Rapanui sediments studied here. That interpretation based on morphometrical phytolith analysis is corroborated by the presence among these samples of that of Poike, which corresponds to the sediment surrounding a charred *Paschaloccocos*[sic] stem.

Grau (2001: 87) noted that, when comparing the small coconuts of *Jubaea* and *Juania*, "we see that that they are not even similar"; on the other hand, Grau saw similarities in the pollen and coconuts of *Jubaea* and the fossil pollen of the Rapa Nui palm (1996:37).

Another possible palm from Rapa Nui noted by Delhon and Orliac (2007: 108) is *Pritchardia pericularum*, subfamily Coryphoideae, tribe Trachycarpeae, subtribe unplaced Trachycarpeae (Baker and Dransfield 2016: 211). The palm from Peru described by Johnson and Mejía (1998) used to make canoes, *Iriartea deltoidea*, is in subfamily Arecoideae, tribe Iriarteeae (Baker and Dransfield 2016:212).

Current research into phylogenetic relationships exhibits both continuity with earlier taxonomic approaches and difference (Dransfield et al. 2005). For an example illustrating this continuity, see Tomlinson et al. (2011). Note that with genetic approaches, shifts in ordering occur. For example, an analysis of 7 WRKY loci illustrated in Meerow et al. (2009, Figure 1 consensus tree) places *Jubaea chilensis* immediately below *Butia*, and above *Attalea*, then descending, *Cocos*, then *Syagrus*. In a subsequent analysis, Meerow et al. (2015) illustrate cladistics relationships using six WRKY gene family loci, showing above *Jubaea chilensis*, first *Butia,* then *Syagrus*, *Lytocaryum*, *Cocos*, and *Attalea*. *Roystonea,* an outgroup, occurs 6 clade lines down from *Jubaea* (Fig. 1, 2015:516). See Asmussen et al. (2006) and Horn et al. (2009) and for additional cladograms related to lamina evolution and plastid DNA phylogeny in related palms. We recommend consulting Fig. 7 in Baker and Dransfield (2016: 223) to see an updated schematic tree of phylogenetic relationships among palms.

Another mode of conceptualizing palm relationships is by considering hybridization results. Many nurseries report on palm hybrids. The recent list shown below is from The Desert Northwest website (2021). In hybrid cross terminology, the female source is listed first, then the male; F2 hybrids are noted by parentheses. Much of the commercial interest in hybrids is to come up with palms that can withstand temperate climate and/or to add ornamental value to the progeny. Below are listed some of several successful crosses with *Jubaea,* a palm that can withstand relatively low temperatures for palms. The Desert Northwest website shows a number of other coccoid hybrids not involving *Jubaea* but intergeneric crosses with some of the genera shown below, such as *Butia eriospatha* × *Syagrus romanzoffiana*. Altogether this site describes 11 cocoid palm hybrid crosses. These involve *Jubaea*:

> *Butia capitata* × *Jubaea chilensis*; *Jubaea chilensis* × *Butia capitata*; (*Jubaea chilensis* × *Butia capitata*) × *Syagrus romanzoffiana*; (*Jubaea chilensis* × *Butia capitata*) × *Jubaea chilensis*; *Jubaea chilensis* × *Syagrus romanzoffiana*; *Syagrus romanzoffiana* × (*Jubaea chilensis* × *Butia capitata*); *Butia eriospatha* × *Jubaea chilensis*.

A caution concerning the hybridization reports above: the crosses should be regarded as anecdotal as they derive from commercial websites and should be checked out against the specialized literature. Incidentally, the chromosome 2n numbers are 32 for *Butia capitate*, *Cocos nucifera*, *Jubaea chilensis*, *Syagrus romanzoffiana* (Dransfield et al. 2008: 62). *Parajubaea* may also be 32 as most of the Attaleinae are 2n = 32. By contrast, *Borassus flabellifer is 2n* = 36 (Dransfield et al. 2008: 60), *Iriartea deltoidea* is 2n = 32, and Roystonea is 2n = 36 (Dransfield et al. 2008: 61). We could not locate the chromosome number of *Juania australis*, but members of the tribe Ceroxyleae are 2n = 30, 32, and 36 (Dransfield et al. 2008: 55).

A website for Sea Breeze Nurseries (accessed October 9, 2016, but no longer available) listed a *Jubaea chilensis* × *Parajubaea cocoides* hybrid. We have not found verified *Cocos* crosses with *Jubaea*, although one website mulls over one questionable possibility. With *Cocos*, there are continuing intraspecies hybridizations being attempted.

We reference the information above to indicate the taxonomic and genetic closeness of the tribe Cocoeae, including Rapa Nui predecessor candidate *Jubaea*. Perhaps *Paschalococos disperta* if not directly available as a living palm would easily fit in the cladograms of analyses like Meerow et al. 2009 and 2015. It would seem that the *Paschalococos* pollen and nut shells might contribute DNA to the effort, but according to Dransfield (2021 np, webpage last modified November 12, 2013) "the pollen remains consist of the almost indestructible sporopollinin pollen cell walls, but no contents where DNA would be and the nuts consist of hard woody dead cells virtually devoid of cell contents—and hence no DNA" (also see Rull et al. 2010: 57). Maybe archaeologists will get lucky and recover some completely preserved nuts so DNA-based comparisons with tribe Cocoeae can be made.

7 Conclusions

Palms of the tribe Cocoeae, though magnificent donors to the production of endless cultural products—nuts, copra, oil, sap, sago, palm cabbage, palm hearts, sugar, flour, honey, wine, butter, milk, cream, water, animal feed (from sap—Dalibard 2009), cosmetics, thatch, coir, string, rope, fuel, lumber, to name a few (see Jones 1995 for an extensive discussion of palm products)—may not be the best of sources for seagoing rafts and voyaging canoes. We suggest that on Rapa Nui, when the large palm called *Paschalococos disperta*, a potential member of the tribe Cocoeae, went extinct for whatever cause or causes, the loss of the palm did not cancel the ability of the Rapanui to maintain Pacific contact with other islands. While large palms have been documented for what might be dubbed "temporary watercraft." Rather, for Pacific voyaging, large true dicots (Eudicotyledons) or gymnosperm trees would be needed. Elsewhere we have argued that the species of large trees used for Polynesian voyaging canoes actually never grew on Rapa Nui (Ingersoll and Ingersoll 2019) and thus did not have the opportunity to become extinct via deforestation. Even the small canoes seen on Rapa Nui may have been built of wood from beyond the island. Thompson wrote:

> There are no canoes in use at the present time, but we found two very old ones in a cave on the west coast, having long ago passed their days of usefulness on the water and now serving as burial cases. They were a patchwork of several kinds of wood sewed together, and though in an advanced stage of dry-rot the material was sufficiently well preserved to prove that it never grew on Easter Island, but had been obtained from the drift-wood on the beach. [1891:474]

While palms can be and are used for lumber, we think the applications, due to the lower density structure of the palm central cylinder and its high moisture and nutrient content, are somewhat limited. The relatively thin cortex limits the dimensions achievable in the lumber. Diverse sources note the susceptibility of the palm stem to rapid deterioration, thus limiting outside uses without preservatives. While we initially were dubious that palms might suffice as rollers for the *moai*, due to the low density of the central cylinders, experiments by Van Tilburg demonstrate otherwise.

Because palms exhibit very different structural characteristics from true dicots and gymnosperm trees, that is, no tree rings, dendrochronology is not possible. The degree of inbuilt age in palms we maintain should be tested by experiment rather than assumed.

We conclude with observations on the tribe Cocoeae to call attention to the close structural relationships among the members of the tribe, which may help to anticipate the characteristics of *Paschalococos disperta*.

Acknowledgments Thanks to Conrad Helms and Brenda Rodgers for obtaining journal articles. The excellent comments of manuscript reviewer Georg Zizka were greatly appreciated, especially in regard to updating classification data.

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Chapter 16
Spatio-Temporal Patterns of Deforestation, Settlement, and Land Use on Easter Island Prior to European Arrivals

Peter Steiglechner and Agostino Merico

1 Introduction

The ecological and socio-economic history of Easter Island prior to European contact exerts a great fascination on both scholars and general public. The reconstruction of this history is primarily based on palaeoecological and archaeological data. Changes in forest patterns and land use, for example, are typically inferred from palynological indicators (Flenley and King 1984; Flenley et al. 1991; Mann et al. 2008), radiocarbon-based dates of charcoal remains (Mieth and Bork 2005; Hunt and Lipo 2006; Rolett and Diamond 2004; Mulrooney 2013), archaeological artefacts (Van Tilburg 1994; Martinsson-Wallin and Crockford 2001), and relicts of formerly cultivated gardens (Wozniak 1999; Stevenson et al. 2002; Bork et al. 2004; Ladefoged et al. 2013). Uncertainties affecting proxy data, however, can lead to difficult interpretations and conflicting views. While the existence of widespread deforestation is uncontested, there is less consensus in relation to

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Electronic Supplementary Material The online version contains supplementary material available at (https://doi.org/10.1007/978-3-030-91127_16).

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_16

timing (Hunt 2007), spatial extent (Rull 2020), and causes (Mieth and Bork 2010) of deforestation. Early results based on coarsely resolved pollen analysis (Flenley and King 1984; Flenley et al. 1991), for example, suggested a somewhat abrupt decline of the forest. A more comprehensive and recent dataset of pollen records suggested, instead, gradual and patchy patterns of deforestation (Rull 2020). Remains of tree stumps and charcoal led scholars (e.g. Mieth and Bork 2015; Bahn and Flenley 2017) to attribute the disappearance of the forest to anthropogenic activities such as the use of trees for tools and construction, for extracting sugary sap, or for clearing land for agriculture through slash-and-burn. The role played by rats in the deforestation—they were probably brought in intentionally as a food item by the first Polynesian settlers (Matisoo-Smith and Robins 2004)—is also subject to different interpretations (Hunt 2007; Mieth and Bork 2010). More recently, deforestation has been attributed to more complex climate–human–landscape feedbacks (Rull 2020, 2021). While the replacement of cleared land by agriculture (often in the form of lithic mulched gardens) appears well documented and undisputed (Bork et al. 2004; Ladefoged et al. 2013), soil characteristics such as fertility, important for determining the relevance of agricultural practices, are less understood, leading to large variations in the estimates related to the maximum number of individuals that could have been sustained by the environment (Puleston et al. 2017).

Although it seems clear that deforestation patterns varied among locations (Rull 2020), contrasting conclusions persist on whether land use and human population patterns were uniform throughout the island (Mulrooney 2013) or whether they varied between regions with some areas being fully abandoned prior to European contact (Stevenson et al. 2015). Motivated by these uncertainties and gaps, studies focused on regional spatial patterns are currently gaining momentum, especially thanks to the use of modern techniques and systematic data analysis. For example, Ladefoged et al. (2013) used satellite image analysis to identify garden structures, and DiNapoli et al. (2019) used point-pattern analysis to explain the distribution of *ahu*, raised platforms made of fitted stones and rubbles hosting the monumental statues called *moai*. Assuming that *ahu* platforms indicate control over limited resources, DiNapoli et al. (2019) found that their distribution is best explained by the proximity to tidal freshwater sources along the coast. The investigation of spatial heterogeneities in terms of environmental features and population dynamics is expected to become an exciting avenue of research in the near future (Merico 2017; Rull 2021).

By integrating different processes and scanty information, mathematical modelling played quite an important role in the reconstruction of Easter Island history. Modelling studies on Easter Island started more than two decades ago with the pioneering work of Brander and Taylor (1998). With an ordinary differential equation (ODE) model, designed as a Lotka–Volterra predator–prey system, in which the human population is the predator and the resource is the prey, Brander and Taylor (1998) showed that a population increase followed by a rapid decline was inevitable when the palm forest was assumed to have a regeneration rate slower than the harvest rate. Later modelling studies extended the work of Brander and Taylor

(1998) in several ways, for example, by considering complex economic processes (Anderies 2000), conflict about resources (Reuveny and Maxwell 2001), complex economic and social structures (Dalton et al. 2005; Good and Reuveny 2006), trade with another society (Roman et al. 2017), multiple resources (D'Alessandro 2007), and Polynesian rats (Basener et al. 2008). While these models undeniably contributed to the understanding and developing of Easter Island narratives, they exhibited certain gaps and shortcomings (Merico 2017) in at least three respects. First, despite introducing different details, they are all grounded on the same designing principle, a Lotka–Volterra type of system with a non- or slowly renewable resource, and are, thus, bound to produce an island-wide boom-and-bust dynamics for a broad area of the parameter space. This resource is often represented by palm trees (as in Brander and Taylor's original work), although there is, admittedly, scarce justification to model trees as preys in a way that the human population ultimately depends on them for their survival. Second, given the uncertainties associated with processes and parameters, such models may produce results that are compatible with multiple narratives (Brandt and Merico 2015). Third, they are all based on the same approach, whereby a set of ODEs reflects the dynamics of island-wide aggregate populations without concerns for environmental heterogeneities, differential impacts of such heterogeneities on local populations, or interactions among individuals.

With the ability to create diversified agents that interact on and with a heterogeneous environment, agent-based models (ABMs) represent an alternative approach to ODE models. ABMs are often used to describe how macroscopic system behaviours emerge from the interaction of microscopic agents with their local environment. For social systems, agents typically represent individual humans (or groups of humans) that interact with one another and with a local environment based on heuristic rules. These rules are typically heterogeneous, non-linear (e.g., discontinuous or discrete), stochastic, time-dependent, and adaptive and might also be memory- and path-dependent (Bonabeau 2002). Agent-based frameworks present, therefore, an interesting alternative with regard to system-wide, aggregate population models in that they can describe systems that, for example, exhibit emergent behaviour or are computationally irreducible (Bookstaber 2017). As such, ABMs offer a more realistic simulative framework to investigate how independent individuals can act in the face of resource constraints, uncertainties, stress, or crisis, to "generate" collective dynamics (Epstein 1999). ABMs should not be seen purely as tools for accurately reproducing the trajectories of observed data. By setting assumptions on the microscopic level of humans and by generating or inferring potential macroscopic phenomena from these assumptions, ABMs create their unique narratives, which can be scrutinised against our understanding of the system under study (Bookstaber 2017).

An example of such tools is the "Artificial Anasazi" model (Dean et al. 2000; Axtell et al. 2002). This model reproduced the population dynamics in the Long House Valley in the Black Mesa area of northeastern Arizona (U.S.), between 800 and 1350 A.D. The study not only showed that the agent-based simulation approach could replicate settlement patterns and rapid population decline, but also that the abandonment of the valley could not be explained solely by environmental constraints; agent heterogeneity in relation to institutional or cultural factors was a crucial modelling feature for matching the observations (Axtell et al. 2002). Other ancient societies studied with ABMs include the Maya (Heckbert 2013) and the Minoan civilisation in Crete, Greece, during the Bronze Age (Chliaoutakis and Chalkiadakis 2016, 2020). No ABMs have been developed so far to study Easter Island's history (Merico 2017). Given the possibilities for regionally different settlement patterns (Stevenson et al. 2015), environmental variations in terms of soil fertility (Puleston et al. 2017), and the existence of autonomous, independent groups, organised into different levels of social structures like clans, *mata* (Van Tilburg 1994), then agent-based models represent a fresh and appealing possibility for the study of Easter Island.

Here we present a new agent-based model of human–resource interactions based on an environment characterised by real geographic and orographic features of Easter Island. Agents represent households of a variable number of individuals located in the environment from which they harvest two resources: (1) trees, which we assume to be non-renewable, and (2) sweet potatoes, which are cultivated in gardens of specified areas. Over time, as agents use trees and cultivate more and more gardens, the population grows and heterogeneous patterns of deforestation and land use emerge. With the model, we investigate the effects of (1) spatial restrictions in relation to resource access and (2) agent's knowledge in relation to environmental features on the spatial and temporal patterns of deforestation, settlement, and land use. With the objective of fostering reproducibility, transparency, and flow of ideas, we make the model available as open-source software (https://github.com/systemsecologygroup/EasterIslandABM) so that it can be used, modified, and redistributed freely. The rest of the chapter is structured as follows. In Sect. 2, we describe the model in general terms, and full details can be found in the Electronic Supplementary Material, which includes an Overview, Design concepts, and Details (ODD) protocol (Grimm et al. 2006, 2020). The results of the study are presented in Sect. 3. In Sect. 4, we discuss the results and outline potential future avenues of model developments. We close the chapter with concluding remarks in Sect. 5.

2 The Model

2.1 Overview

We developed an agent-based model (ABM) that simulates the spatial and temporal dynamics of household agents and their interactions with the natural environment through resource consumption on Easter Island prior to European arrival. The environment is encoded on a 2D discretised map with real geographic and orographic features. Agents are represented by households, which comprise a variable number of individuals. Households rely on two resources: (1) palm trees, considered here a primary, non-renewable resource for essential tools, firewood, building material, sugary sap, etc. (e.g. Bahn and Flenley 2017) and (2) cultivated gardens of sweet potatoes, which constituted an important source of carbohydrates and water on the island (Tromp and Dudgeon 2015). Households use these resources by cutting trees and by creating gardens (i.e., by cultivating cleared, arable land available in their immediate surrounding). The growth or decline of households depends on the success with which they can obtain these resources. Households adapt to the changing environment and to the growing population in three ways. First, a household splits into two when it becomes too large and one of the two relocates in a different place. Second, households relocate when resources become scarce in their current location. Their moving behaviour is determined by resource availability and certain features of the environment, including elevation and distance from the three major lakes (Rano Kau, Rano Raraku, and Rano Aroi). Third, in response to the declining number of trees, households adapt their resource preference from a resource combination dominated by trees to a combination dominated by stable cultivation of sweet potatoes. In summary, the interaction between agents and the natural environment and the adaptive response of agents shape settlement patterns and population dynamics on the island.

In accordance with Vargas et al. (2006) and Bahn and Flenley (2017), the simulations start with two households (comprising a total population of 40 individuals) positioned in the proximity of Anakena Beach in the northern part of the island, in the year 800 A.D., thus mimicking the arrival of the first Polynesian settlers. Model updates occur asynchronously on time steps of one year until 1800 A.D. The model does not include processes such as spreading of diseases or slavery that were introduced after the discovery of the island by European voyagers in the eighteenth century. A schematic of the model is presented in Fig. 16.1. The model is coded in python, and the full code is freely accessible from GitHub https://github.com/systemsecologygroup/EasterIslandABM. A table including all parameters, their values, and sources can be found in Electronic Supplementary Material, Sect. 2. An Overview, Design concepts, and Details (ODD) protocol (Grimm et al. 2006, 2020) of the model, which contains all implementation details, is presented in Electronic Supplementary Material, Sect. 4.

2.2 Environment

The environment is encoded as a collection of Delaunay, triangular cells (with a constant area of $57.4 \cdot 10^3$ m^2) covering the island's total area of 167.4 km^2. These cells provide a detailed, discretised representation of the island's actual orographic properties: elevation and slope. In addition, the environment includes the three crater lakes, Rano Kau, Rano Raraku, and Rano Aroi, which represented the only permanent source of freshwater on the island (Rull 2020). Following palynological evidence (Rull 2020), we externally force the aridification of Rano Raraku during two periods, from the arrival of the first settlers in 800 to 1200 A.D. and from

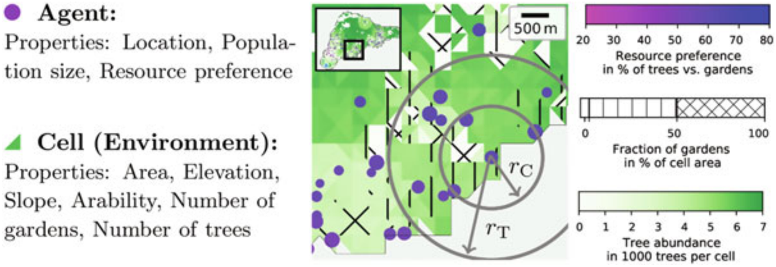

Fig. 16.1 Schematic of the model setup. Agents are characterised by their locations (dots), their population sizes (dot size), and their resource preferences (dot colour). The agents' surroundings (concentric circles) are defined by the tree harvest radius r_T and the cultivation radius r_C for cultivating gardens. Agents and their behaviour are described in detail in Sect. 2.3. The environment is subdivided into Delaunay triangular cells. Cells are characterised by fixed orographic and geographic features (area, elevation, slope, and arability index) and variable amounts of resources (the number of trees and number of cultivated gardens). The environment and its features are described in detail in Sect. 2.2

1570 to 1720 A.D. The discretisation method followed to create the environment is described in full detail in Electronic Supplementary Material, Sect. 4.3.1. A cell can provide two resources: (1) a variable number of trees and (2) a specific yield of sweet potatoes according to a cell's fixed arability index.

2.2.1 Palm Trees

A total of 16 million palm trees are uniformly distributed on the island at the start of a simulation, following Mieth and Bork (2015). Cells that are either too steep or too high in altitude are left empty (Fig. 16.2a). Thus, at the start of a simulation, 85% of the island is covered with trees. The number of trees in a cell can decrease over time as agents cut them down either for specific uses of the wood or simply to clear land for cultivation (see Sect. 2.3.1). To reflect the combined detrimental impact that human activities and Polynesian rats had on the regeneration of the forest (Hunt 2007; Bahn and Flenley 2017), palm trees are assumed to be a non-renewable resource.

2.2.2 Sweet Potatoes

As mentioned above, sweet potatoes constituted an important source of carbohydrates and water for the Rapa Nui, especially during the last centuries prior to European contact (Louwagie et al. 2006; Stevenson et al. 2015; Tromp and Dudgeon 2015). Archaeological evidence (e.g. Hunt and Lipo 2011; Ladefoged et al. 2013; Rull 2020) shows signs of agricultural activities organised on patchy, metre-scale areas called *manavai* (gardens). In our model, a garden is represented by a cleared,

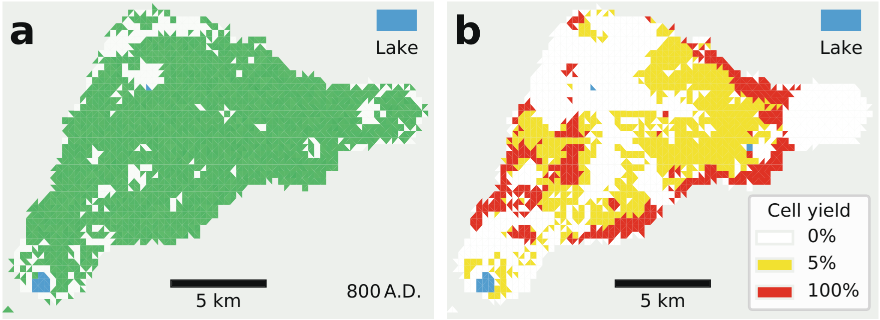

Fig. 16.2 Features of the environment related to the two resources: (**a**) initial distribution of trees and (**b**) cell arability in % yield of sweet potatoes. At the beginning of the simulation (800 A.D.), a total of 16 million trees are uniformly distributed on the map, covering 85% of the island. Each cell contains about 5500 trees. The classification of cells into "well-suited" (100%yield), "poorly suited" (5% yield), and "not suited" (0% yield) for cultivating sweet potatoes is based on the agriculturally viable zones identified by Puleston et al. (2017)

cultivated area of 1000 m^2 on an arable cell. At each time step, cultivation of such gardens provides agents with a constant yield of sweet potatoes. Given the cell's area of $57.4 \cdot 10^3$ m^2, one arable cell can host up to 57 gardens. Cells are characterised by a fixed arability index, which defines the suitability of a cell for cultivating sweet potatoes or, more specifically, the cell yield for sweet potatoes. We considered three categories: "well-suited" (100% yield), "poorly suited" (5% yield), and "not suited" (0% yield). To assign a specific arability index to a cell on the map, we considered the agriculturally viable zones identified by Puleston et al. (2017), based on the previous studies (Ladefoged et al. 2009, 2013; Louwagie et al. 2006). Following this approach, we obtain that "well-suited," "poorly suited," and "not suited" cells cover, respectively, 16%, 33%, and 51% of the island (Fig. 16.2b). In summary, through the opportunity to cultivate gardens in well-suited and in poorly suited cells, the environment provides agents with a stable, non-degrading second resource, sweet potatoes.

2.3 *Agent Characteristics and Behaviour*

A single agent in the model is represented by a household with a variable number of individuals, up to a maximum of 36 individuals, who live and harvest resources together as a single entity. An agent is characterised by three main properties: (1) the location on the island, (2) the number of individuals comprising the household, and (3) the resource preference (share of using palm trees over cultivated gardens). In each time step, which represents one year in the simulation, all agents are updated sequentially and in random order. During an update, the household interacts with its surrounding environment by cutting trees within a tree harvest radius r_T and by cultivating gardens within a cultivation radius r_C (Fig. 16.1 and Sect. 2.3.1). The number of individuals composing a household agent grows or declines according to a satisfaction index related to their resource harvest (Sect. 2.3.2). A household agent responds to changes in population size and local resource availability via three adaptation mechanisms: (1) splitting (and thereby creating a new agent), when the number of individuals reaches a maximum of 36, (2) moving to a new location, when a new agent is created or when the satisfaction index is too low due to insufficient resource harvests, and (3) updating the resource preference (i.e., the share of using palm trees over cultivated gardens) in response to local deforestation (Sect. 2.3.3).

2.3.1 Resource Requirement, Preference, and Harvest

For growing, a household is required to harvest a certain number of trees and a certain amount of sweet potatoes at every time step. Although humans did not consume trees directly, we posit that their primary use was destructive and essential for a household, e.g., to provide firewood and timber for building tools, and thus we assume that both resources play an equivalent role for the survival of agents and, over time, one resource can replace the other. This means that, in theory, an agent can harvest the required amount of resources either solely from trees (for a maximum of 10 trees per individual per year, Brandt and Merico 2015) or solely from continuously cultivated gardens (for a maximum of 6.79 gardens per individual, Puleston et al. 2017, weighted by the arability index, see derivation in Electronic Supplementary Material, Sect. 1). In practice, households always require a combination of both resources. The share of trees in this combination is determined by the resource preference of the household, which is bounded between 20% and 80%. The share of cultivated sweet potatoes follows accordingly. If, for example, the resource preference is 35%, then the requirements for using trees and cultivating gardens are 35% × 10 trees per individual per year and 65% × 6.79 gardens (weighted by their arability index) per individual, respectively. Thus, the population size and the current resource preference determine the combination of resources a household requires at every time step. In each update, an agent harvests resources sequentially, first from cultivated gardens and then from cutting trees.

Agents cultivate multiple gardens in arable cells and, at each time step, obtain an immediate, constant yield from them. If, at a time t, an agent requires more sweet potatoes than it required in the previous time step (for example, due to an increase in the number of individuals comprising the household or due to a decrease of its resource preference, following a decrease in the number of trees nearby), then the agent tries to increase the number of cultivated gardens. To cultivate new gardens, an agent needs to find a cell with the following characteristics: (1) it must be within the cultivation radius, (2) it must be well-suited for cultivating sweet potatoes, (3) it must contain an area of at least $1000\,\mathrm{m}^2$ (the area of a garden) that is clear of trees and not yet cultivated. Since at the start of a simulation, trees are distributed uniformly within cells, the amount of cleared land in a cell corresponds to the fraction of removed trees at time t. Cleared land, however, may already include cultivated gardens. If no cell fulfils the three conditions, the agent clears land in one cell by slash-and-burn until the conditions are met. In this case, among all potential cells, the agent chooses the cell in which the least number of trees needs to be removed. If no cell fulfils all these conditions, the agent considers poorly suited cells (i.e., cells with a lower arability index and, thus, a smaller yield for sweet potatoes) as well. The cultivation of such low-yield areas is not limited by labour demand in this model. Gardens are cultivated continuously (i.e., fallowing is not considered). This sequential addition of gardens continues until the resource requirement of the household for sweet potatoes is met, or until no more suitable cells can be found.

After agents have tried to meet their resource requirement for cultivated gardens, they begin to satisfy their requirement for trees by cutting them down. To cut trees down, an agent needs to find a cell with the following, obvious characteristics: (1) it must be within the tree harvest radius and (2) it must contain trees. An agent cuts trees down until its resource requirement for trees is met or until the surrounding area is devoid of trees.

2.3.2 Population Dynamics

Over time, the population of a household increases or decreases depending on its success at harvesting the two resources. The success of an agent is limited by the smaller ratio between actual harvest and required harvest for both resources (trees and cultivated gardens), according to the Liebig's law of the minimum. Therefore, an agent is fully successful if both resource requirements are fulfilled and fully unsuccessful if one of the two resources could not be harvested at all. In particular, an agent is fully unsuccessful if it cannot find trees for building tools and other needs despite having been successful at harvesting the required amount of sweet potatoes, and vice versa.

Following previous modelling studies that assumed the rate of population growth to be maximal when resource consumption exceeds a certain threshold and to be reduced (or to be even negative) when resource consumption is insufficient (Lee and Tuljapurkar 2008; Puleston and Tuljapurkar 2008), we define an expected net population growth rate for a household as a function of a household satisfaction index, which measures the success of resource harvest over a scale ranging from 0 (fully unsatisfied) to 1 (fully satisfied). The household satisfaction index is calculated as the rolling mean between the success in the previous year and the success in the current year. The maximum expected net growth rate at full satisfaction is assumed to be 100.7% (i.e., 0.7% growth) per year, in line with previous suggestions (Vargas et al. 2006; Bahn and Flenley 2017). If the agent satisfaction declines, the expected net growth rate decreases and the household grows at reduced rate or even shrinks when satisfaction falls below a certain threshold. The satisfaction threshold is set at 0.69 (with a growth rate of 100% indicating replacement of the household), following the approach of Puleston et al. (2017) and by assuming that our satisfaction index reflects their "food ratio." For simplicity, we consider linear relationships between the net population growth rate

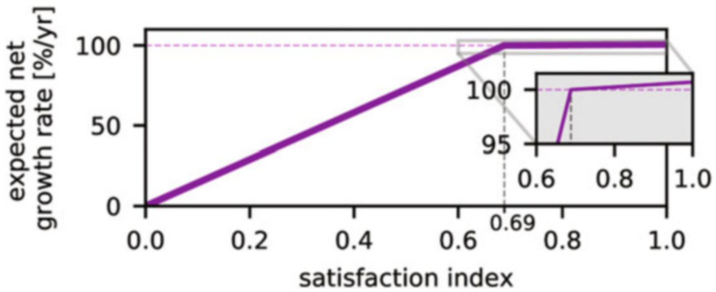

Fig. 16.3 Expected net growth rate of a household as a function of its satisfaction. While the actual population growth process is stochastic, on average a household grows or declines according to this expected net growth rate. The satisfaction threshold below which the population size decreases is 0.69 (marked by the vertical dashed line) and is adopted from a previous demographic modelling study (Puleston et al. 2017). The maximum expected growth rate is set to 100.7% per year (Vargas et al. 2006; Bahn and Flenley 2017)

and the household satisfaction index below and above the satisfaction threshold (Fig. 16.3).

Within a household agent, population growth is not a continuous process because birth and death of individuals are discrete and probabilistic events. These discrete processes are approximated by the household expected net growth rate, which determines, at each time step, the probability of an individual to survive (when the satisfaction index is below 0.69) or to reproduce (when the satisfaction index is above 0.69). For example, when a household has a continuous maximum expected net growth rate of 100.7% per year, its population size remains constant during most years and increases by 1, 2, or more individuals in some, rare time steps such that, on average, the household grows or declines according to the expected net growth rate. We finally note that if a household population decreases, that household may need fewer gardens to harvest a sufficient amount of sweet potatoes and can, thus, free the redundant gardens for other agents. A more detailed and technical description of these processes can be found in Electronic Supplementary Material, Sect. 4.3.3.4.

2.3.3 Adaptation Mechanisms

As agents harvest resources, they grow and the environment changes. Agents adapt to population growth and environmental change with three mechanisms: splitting, relocating, and updating the resource preference.

A household agent splits when its population size exceeds a maximum of 36 individuals. When this maximum is exceeded, a fixed number of 12 individuals split off from this household to form a new agent in a new location. If the population size of an agent falls below a minimum of 6 individuals, the household dies and is removed from the system.

Agents move to a new location if (1) they split off from an existing household or (2) the agent's satisfaction is below the threshold of 0.69 (Fig. 16.3) and its current success in resource harvest does not indicate rapid improvement for the next time step. To choose a new location, agents evaluate cells according to location preferences. We assume that agents prefer cells (1) with low elevation and low slope, (2) in the proximity of one of the three lakes, weighted by the area of the lake, (3) with low population density within the cultivation radius, (4) with high availability of trees within the tree harvest radius, and (5) with high availability of uncultivated and highly arable gardens within the cultivation radius. Note that only the last two preferences are directly related to the amount of resources an agent can access from the new location. The other preferences have only an indirect relevance for population growth or survival and may reflect decision-making based on heuristics or may account for factors that are not explicitly included in the model (such as easy access to fishing activities). Instead of finding an optimal location with respect to the location preferences, agents move according to a probabilistic decision-making approach, whereby cells with better characteristics in relation to the preferences are also those more likely to be chosen as new locations. This probabilistic approach reflects, for example, different views within the same household about the new location when an agent takes moving decisions. Note that after moving, conditions in the new location might change quickly as more agents may decide to move to the same area and, thus, impact the local environment. A more detailed description of the moving process can be found in Electronic Supplementary Material, Sects. 4.3.3.9 and 4.3.3.10.

The resource preference of an agent determines the share of using palm trees over cultivating gardens in the next time step. This property changes linearly as a function of local deforestation and is bounded between a minimum (20%) and a maximum (80%). This adaptation mechanism reflects the fact that the Rapa Nui initially relied on the destructive use of abundant palm trees and other natural resources and that agricultural activities increasingly replaced this dependency as deforestation progressed over time (e.g. Louwagie et al. 2006; Mulrooney 2013). The minimum resource preference of 20% is based on the assumption that people could not survive without trees even if agriculture would provide sufficient food resources.

2.4 Simulations and Sensitivity Analysis

To investigate the relative importance of different processes to the overall temporal and spatial dynamics of the agents on the island, we created three scenarios corresponding to three different model formulations. In the first scenario, named "unconstrained," households are neither limited by any spatial restrictions for harvesting trees and for cultivating gardens nor by any location preferences. Thus, agents consider all locations on the island equally suitable for settling. In the second scenario, named "partly constrained," access to resources is restricted within specified radii ($r_T = 2$ km and $r_C = 1$ km) and, as in the previous scenario, the moving of households is not influenced by location preferences. In the third and final scenario, named "fully constrained," access to resources is restricted within specified radii ($r_T = 2$ km and $r_C = 1$ km) and the moving of households is influenced by location preferences, which are based on environmental features. The three scenarios and their specific features are summarised in Table 16.1. To account for the stochastic nature of our model, we run 50 replicate simulations for each scenario.

Since our investigation is focused on the heterogeneity of population patterns on the island, we present the results as snapshots of the spatial distribution of trees, cultivated gardens, and agents for a single, representative simulation run at different times (or at all time steps in the video in Electronic Supplementary Material). In addition, we divide the island into a number of regions, as shown in Fig. 16.4, defined according to geographic characteristics, like elevation (e.g., the region *Uplands* comprises locations above the altitude of 100 m), distance from lakes (regions *Raraku* and *Kau*), or particular points of interest (e.g., *Anakena*). This

Table 16.1 Summary of the different scenarios considered in this modelling study

Scenario	Resource access	Location preferences
Unconstrained	Whole island	None
Partly constrained	Within radii r_T and r_C	None
Fully constrained	Within radii r_T and r_C	All

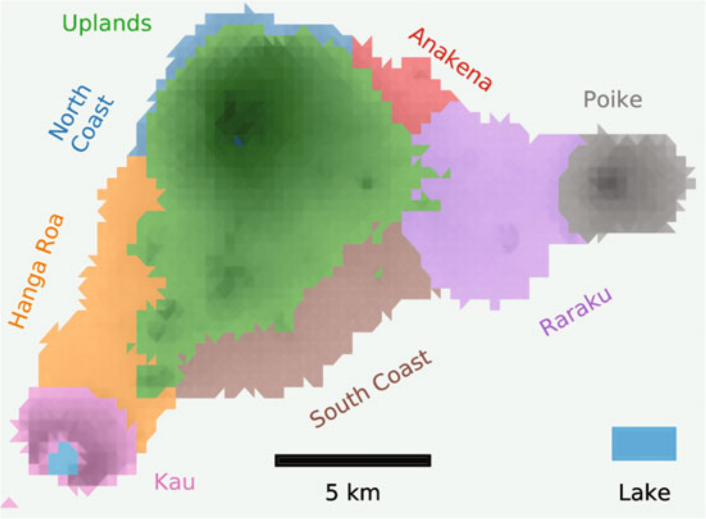

Fig. 16.4 To investigate the effects of environmental heterogeneity on population dynamics in our model, we divide the island into eight regions and present the results both as globally aggregated and regionally aggregated temporal patterns. The same colour-coding adopted here is used for showing the results in the corresponding regions (Fig. 16.5)

allows us to quantitatively compare the different population dynamics obtained in these different regions.

We complement our investigations with a sensitivity analysis of the model results in relation to specific model assumptions. There are many interesting insights one can infer from these analyses. Here, we focus our attention on the effects of parameters and processes to timing and size of a global population peak, obtained under the "fully constrained" scenario. We explore the effects of ±50% changes in the values of some crucial parameters: (1) maximum requirement for trees per individual per year, (2) maximum requirement for cultivated gardens per individual, and (3) resource access radii. In addition, we explore the effects of (1) different initial tree distributions, (2) droughts of Rano Raraku, and (3) minimum share of using trees over cultivating gardens.

3 Results

3.1 Scenarios

As explained in the previous section, to investigate the relative importance of different processes to the overall temporal and spatial dynamics of the agents in our model, we explored three scenarios, corresponding to three different model formulations (Table 16.1).

In the first scenario, "unconstrained," agents can access resources (use trees and cultivate sweet potatoes) anywhere on the island without any spatial restrictions or location preferences. Therefore, during the first centuries, households populate the island uniformly (Fig. 16.5a1). By the sixteenth century, on the global scale, the human population has reached its peak at around 8000 individuals, arable land has become scarce, as roughly half of the island gets occupied by a total of approximately 82,000 gardens (the maximum number of gardens that the island can sustain, which includes well-suited and poorly suited gardens, the latter with a very low yield of sweet potatoes), and almost 80% of the palm trees have disappeared (Fig. 16.5a2). The shift in resource preferences characterised by larger shares of garden cultivation over palm trees leads to an initial, small decline in population size, right after the population peak. From about 1600 to about 1700 A.D., the island is in a phase characterised by a relatively stable population size of about 7000 individuals relying for livelihood on the maximum possible number of cultivated gardens (Fig. 16.5a2). The minimum requirement for trees, however, causes a rapid collapse of the population once the island is deforested (shortly after 1700 A.D.) The population crash is immediately followed by a rapid decline in the number of cultivated gardens. The regional population patterns (Fig. 16.5a3) are very similar in shape to the global pattern.

In the second scenario, "partly constrained," agents can access resources only within specific spatial limits from their locations. During the first centuries, on

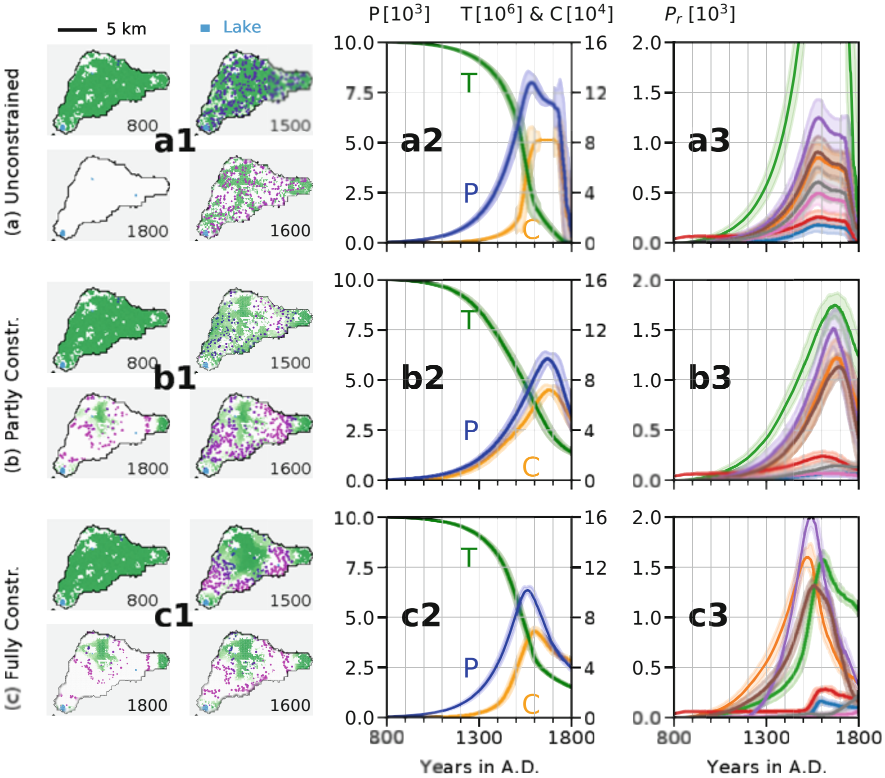

Fig. 16.5 Simulation results for the three scenarios: (**a**) unconstrained, (**b**) partly constrained, and (**c**) fully constrained. The left column (1) shows spatial snapshots of the results for corresponding scenarios at four different times, 800, 1500, 1600, 1800 A.D. These snapshots show: tree cover (green), density of occupied gardens (hatch lines), and agents (dots). The size of the dot reflects the number of individuals comprising the household. The colour of the dot reflects the resource preference of the household (decreasing resource preference for trees over cultivated gardens goes from blue to pink). The middle column (2) shows island-wide aggregates of the total population in thousand individuals, P (blue), the number of trees in millions, T (green), and cultivated gardens in ten thousand, C (orange). The thick lines represent averages of ensembles of 50 runs. The semi-transparent areas indicate the standard deviation of the ensemble runs. The right column (3) shows the dynamics of population sizes in thousands, P_r, aggregated in each region separately. The colours correspond to the specific regions defined in Fig. 16.4 (green: *Uplands*, violet: *Raraku*, orange: *Hanga Roa*, brown: *South Coast*, grey: *Poike*, red: *Anakena*, pink: *Kau*, and blue: *North Coast*)

the global scale, agents increase in numbers, occupy new locations randomly (Fig. 16.5b1), and settle in these locations for as long as their satisfaction index remains sufficiently high. In this phase, agents do not compete much with one another for resources that are abundant and distributed over the whole island. In contrast to the previous scenario, we observe now a less homogeneous distribution of agents (Fig. 16.5b1) because, as the number of agents increases, environmental differences in terms of resource availability become more pronounced. Under these conditions, the search for new locations slows down population growth, leading to a prolonged and slow period of growth that lasts until almost 1700 A.D. (Fig. 16.5b2). Regions with a higher number of cells well-suited for cultivation (Fig. 16.2b) sustain larger population densities (Fig. 16.5b1). However, regions that become highly populated are also those that experience a more severe environmental degradation in terms of tree reduction (Fig. 16.5b1), thus imposing a stronger pressure on agents to adapt. In contrast, regions with a small but still a sufficient number of arable cells (e.g., parts of the *Uplands* or *Kau*) host fewer agents per area throughout the whole simulation period (compare Figs. 16.5b3 and 16.5a3). The environment of these regions is degraded at a slow pace, and the local agent population tends to remain more stable than in other regions. However, as resources become scarce in large parts of the island, agents start to compete with one another more intensively. Newly created households or households dissatisfied with their resource harvest start to move to populated regions if such regions can still provide the necessary resources. Agents begin to cluster more strongly around 1600 A.D., so that pressure increases on resources in more and more regions (Fig. 16.5b1), initiating cascade-like population declines (Fig. 16.5b3). The island-wide population is halved within a century and is immediately followed by a similar decline in the number of cultivated gardens (Fig. 16.5b2).

Under the "fully constrained" scenario, agents can access resources only within specific spatial limits from their locations and, in addition, they have preferences for specific environmental features, thus qualitatively mimicking human decision-making when moving to new locations. Under these conditions, a quick clustering of agents is observed within more preferred regions like *Hanga Roa*, *South Coast*, and *Raraku* due to their overall high arability (Figs. 16.5c1 and 16.2b) or other attractive geographical features. These more densely populated regions are, thus, subject to increased deforestation in the early centuries. This increases the speed with which agents adapt to the disappearing forest via a transition to garden cultivation activities. The increasing number of cultivated gardens exacerbates forest clearance, thus establishing a positive feedback loop of deforestation in some locations (arability Fig. 16.5c1). In contrast to the two previous scenarios, clustered agents now compete over the common resources in local areas well before a large-scale (or island-wide) resource shortage develops. The global population peaks at 6000 individuals before 1600 A.D. (Fig. 16.5c2), roughly a century earlier than in the "partly constrained" scenario and at a slightly higher value. After this peak, the population decreases at a rate slower than in the previous scenario and is reduced by 50% within two centuries. During this period, the clusters of high population densities move from initially preferred but now depleted regions to less exploited regions (Fig. 16.5c1). Only in this scenario, we observe clear differences in the population dynamics of different regions (Fig. 16.5c3). For example, while the populations of the *Uplands*, *North Coast*, and *Anakena* enter a phase of slow demise around 1600 A.D., by this time the populations of *Raraku* and *Hanga Roa* had already entered a phase of abrupt decline, more in line with the previous scenario. In contrast, the relatively small populations of *Kau* and *Poike* increase continuously

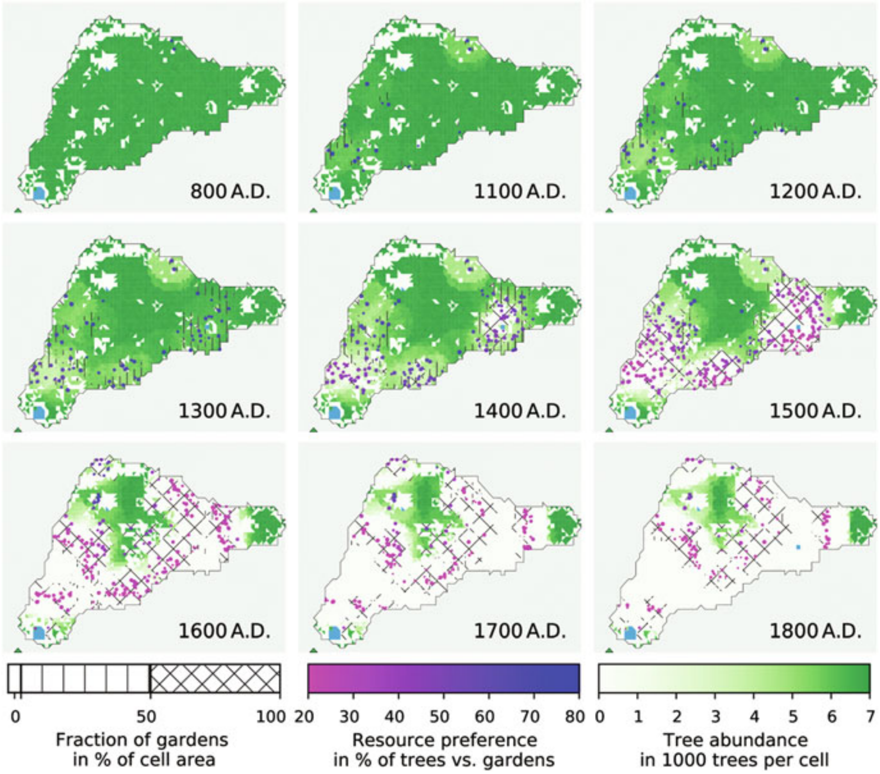

Fig. 16.6 Snapshots produced under the "fully constrained" scenario. Each panel shows the distribution of trees (with different green intensities) and the fraction of cultivated garden per cell area (shown as vertical or crisscrossed hatch lines for, respectively, sparse and dense cultivations). Agents are shown as dots, with the number of individuals reflected by the dot size and resource preference reflected by the dot colour. These snapshots can be compared to a collection of similar maps created by Rull (2020, Fig. 9) through the aggregation of spatio-temporal palynological and archaeological information around the three lakes. In the video in Electronic Supplementary Material we show the snapshots of this simulation run for all time steps from 800 to 1800 A.D.

until 1800 A.D. In summary, the different regions show quite different trajectories in terms of population dynamics and deforestation patterns.

Figure 16.6 shows the spatio-temporal patterns in relation to agent distribution, tree cover, and cultivation activities produced under the "fully constrained" scenario. These patterns are qualitatively consistent with a very recent collection of archaeological and palynological information presented by Rull (2020, Fig. 9). In line with these observations, our simulations show a relatively dense tree distribution in the regions around the three lakes. Deforestation around Rano Kau increases in the fourteenth century in both simulations and observations. In our model, some areas around Rano Raraku are already deforested before 1400 A.D., but, similarly to observational evidence, the clearance of trees strongly intensifies in the fifteenth century. The drying out of Rano Raraku (between 1570 and 1720 A.D.) suggested by Rull (2020) coincides in our model results with the disappearance of trees and population decline in this region, but also in the *South Coast* and in the region around *Hanga Roa*. Moreover, similarly to Rull (2020)'s data, the tree density around Rano Aroi remains unaltered in our simulation. Intensified deforestation in the *Uplands* is observed in both model and observations only from 1600 A.D. onwards.

3.2 Sensitivity Analysis

By determining the rate at which household agents need to extract resources, the constant maximum tree and cultivation requirements per individual have an obvious importance on limiting the global population size. A ±50% change in the maximum tree requirement per individual cause a ∓20% change in the peak population size (Fig. 1 in the Electronic Supplementary Material). A 50% increase in the maximum cultivation requirement per individual (corresponding to lower yields from a single garden) produces a decrease by 20% of the peak population size. More significantly, though, a 50% reduction in that parameter leads to a population peak that is delayed by 50 years and that is 50% higher than the peak produced with the standard parameter value (Fig. 2 in the Electronic Supplementary Material).

By restricting the number of potential locations from which an agent can obtain resources, the access radii for tree harvest and cultivation limit the amount of resources an agent can obtain. It is therefore not surprising that for smaller radii, this restriction tends to reduce the population size and vice versa. In fact, a ±50% change in resource search radii produces roughly a ±20% change in population peak values (Fig. 4 in the Electronic Supplementary Material).

The assumption of higher tree densities around the lakes, compared to the uniform distribution adopted in our standard simulations, does not impact island-wide population dynamics unless this clustering is very pronounced and, consequently, locations that provide access to trees are limited to only a few small areas around the lakes. In the case of pronounced clustering, the population peak is delayed by more than 50 years and the maximum value is reduced by 30% (Figs. 5 and 6 in the Electronic Supplementary Material).

In all model scenarios, droughts are simulated by drying out Rano Raraku during the two periods 800–1200 A.D. and 1570–1720 A.D. (Rull 2020). In Fig. 7 in Electronic Supplementary Material, we compare our standard runs, which include droughts, with runs that omit them. At a global scale, the influence of droughts is negligible. At a regional scale, however, the influence of droughts is more pronounced. In our standard runs, agents tend to avoid moving to *Raraku* during the first drought due to its distance from the available water sources (Fig. 8 in the Electronic Supplementary Material). However, after 1200 A.D., between the two droughts, *Raraku* becomes an attractive settlement location with its overall high arability and mostly uncultivated areas. This attractiveness causes a more rapid increase in the population size of the region compared to runs in which droughts are not included. It is important to note, however, that droughts in our model do not influence resources like soil fertility or tree availability but only the moving behaviour of the agents through the preference for lake proximity.

The minimum, non-zero level considered for the resource preference for using trees over cultivating gardens (equivalent to 20%) in our standard simulations is based on the assumption that people could not live without trees. This critical assumption produces the population declines observed in all scenarios and, ultimately, extinction once the island is completely deforested. If, instead, the minimum resource preference is set to 0%, reflecting the possibility that people could perfectly adapt to an environment without trees and sweet potatoes are the only determining factor of survival, then the population size remains constant after it reaches a peak at around 1580 A.D. (see Fig. 9 in the Electronic Supplementary Material) because it can rely 100% on cultivated gardens and soil fertility does not decline by model design.

4 Discussion

With respect to previous modelling works (for reviews, see Reuveny 2012; Merico 2017), the agent-based model presented here adds two elements of novelty: (1) a spatially explicit framework, which includes realistic geographic features and plausible soil characteristics, and (2) independent household agents that interact with their environment through tree harvest and sweet potato cultivation. As time progresses during a simulation, agents take decisions that shape the environment and the changing environment, in turn, affects agents' decisions.

To investigate the relevance of different processes in shaping the interactions between agents and environment, we created three model scenarios. All scenarios share the following conditions. Up to 85% of the island is initially covered with palm trees, in line with uncontested evidence supporting the existence of a dense palm forest prior to human arrival (e.g. Mieth and Bork 2015). Trees are assumed non-renewable to account for the detrimental impact of Polynesian rats (Hunt 2007; Bahn and Flenley 2017). The island is characterised by the overall low soil fertility, consistent with low nitrogen fixation rates suggested by a previous study (Puleston et al. 2017). Soil fertility remains constant throughout the simulations, thus providing stable yields of sweet potatoes. Yields, however, vary from location to location, according to a spatially heterogeneous arability index. Soil fertility is fixed because clear evidence in support of intensive lithic mulching practices on the island (Bork et al. 2004) suggests a continuous and strenuous effort to avoid erosion and maintain soil fertility. Agents are able to replace their initial, strong dependency on a declining forest (and the associated resources, not just essential timber but also fruit, sugary sap, and other forest-derived livelihoods) by the cultivation of new gardens. However, they can do so only up to a certain degree because we assume there is always a minimum, non-zero requirement for trees as a primary resource. Agents share the same objective in all scenarios: they harvest resources in order to maximise their instantaneous population growth.

In the first scenario, "unconstrained," household agents can harvest trees and cultivate gardens anywhere on the island, regardless of the distances from their settlement locations, and can relocate on the island without constraints in terms of resource availability and other geographical preferences. Under such unrealistic conditions, this scenario produces a period of about one century of high (around 7000 individuals) and relatively stable, if not slightly declining, population size. This relative stability is primarily sustained by the continuous and steady supply of sweet potatoes from cultivated gardens. As the forest declines during the first centuries, the number of cultivated gardens increases until the whole arable area (comprising a maximum of about 82,000 gardens) on the island is cultivated. The number of cultivated gardens remains at this maximum level for more than a century because during this period there are enough trees to meet household requirements and soil fertility does not decline over time. Once deforestation is completed, the population collapses to zero and the number of cultivated gardens declines abruptly. This scenario mimics the typical conditions of differential equation-based models (pioneered by Brander and Taylor 1998) in which an assemblage of unspecified individuals, the population, cut trees and practice agriculture anywhere on the island without concerns for practical access to resources or environmental features.

In the second scenario, "partly constrained," agents can harvest trees and cultivate gardens for sweet potatoes only within specified distances from their settlement locations (1 and 2 km for cultivation and trees, respectively), but they can still relocate on the island without constraints in terms of resource availability and other geographical preferences. In the early centuries, as the island is populated less uniformly than in the previous scenario, spatial heterogeneity in the environment leads also to different speeds with which agents can use and deplete resources. Regions with the overall high arability can sustain larger populations than those with the overall lower arability but are also depleted of resources at faster paces than others. Thus, agents in these regions have to adapt faster than in others and, eventually, they move to new locations, where an existing local population already uses the available resources. In other words, the agent objective to maximise instantaneous growth in combination with the constrained resource access of this scenario causes the emergence of intensified competition for new locations as resources become scarce. This leads to a region-by-region, cascade-like resource depletion and population declines. All regions exhibit almost synchronised boom-and-bust dynamics. This scenario produces results that correspond to the island-wide "ecocide" narrative (Flenley and Bahn 2003; Diamond 2005). The growth of a population that has, in the initial phase of the simulation, no concerns for resource availability falls, later, into a spiral of intensified competition for depleting resources and, eventually, into a collapse.

In the "fully constrained" scenario, agents have some form of environmental knowledge in terms of geographical features, which they use to move to locations that meet their geographic and resource-related preferences, thus constraining the random movement from the previous scenarios. This leads to a more effective exploitation of resources, to a consequent rapid population growth in the early centuries, and—in contrast to the previous scenarios—to a rapid and dense clustering of the agents in certain preferred regions. Patterns of resource depletion are quite different in the various regions. Clearly evident is, for example, the coexistence of areas with untouched forest and areas fully devoid of trees. When resources are depleted in one region, agents face relocation to areas that they might have rejected earlier in the simulation, because they could still find places with better characteristics (places with an overall higher arability or other favoured geographic features), but that are now acceptable because these areas provide a sufficient amount of resources. This is observed in particular in the *Uplands*, which cover the largest portion of central territories but remain mostly unpopulated in the early centuries. A relocation behaviour based on environmental knowledge represents, in principle, an effective adaptation strategy in the face of resource shortages. In our model, knowledge leads to an earlier peak and a slower decline of the island-wide population size than in the previous scenario. However, and quite importantly, knowledge of the environment does not avert the tendency of boom-and-bust dynamics on the global scale. This tendency is inevitable and depends on the designing principle of our model—and of any other previous model of Easter Island since the work of Brander and Taylor (1998), see the reviews of Reuveny (2012) and Merico (2017)—that is, agents always maximise growth on the base of a pool of finite and non- or slowly renewable resources. In fact, as in the previous scenarios, the global population dynamics follow the same general Malthusian patterns typical of pre-industrial societies (Clark 2007), an initial exponential growth turns into a decline when resources become scarce. However, in contrast to the other scenarios, the regional patterns of the "fully constrained" scenario vary strongly from one another. For example, some regions show population trajectories that are incongruous with the "ecocide" narrative and more in line with the "slow demise" hypothesis (Brandt and Merico 2015).

Among the three scenarios, we consider the "fully constrained" scenario the most realistic one because it produces spatio-temporal patterns of deforestation that are qualitatively very similar to the archaeological and palynological data summarised in Rull (2020, Fig. 9). Temporal changes in settlement patterns and in the distribution of cultivated areas on the island remain, however, matters of debate. Stevenson et al. (2015), for example, suggested region-specific declines of land use and, presumably, population densities in areas with low arability (corresponding to the *Uplands* region in our model) before European contact. Mulrooney (2013), in contrast, disputed the notion of a widespread shift of human settlements prior to European contact. Our results suggest that it is not only the heterogeneity of the environment to be relevant but also the way people responded to it. The condition of choosing locations based on environmental preferences, which we included in the "fully constrained" scenario, implies a profound knowledge of the environment—a plausible assumption given the small size of the island and given the form of governance that the monument construction and the rituals associated with it might have provided (Lipo et al. 2020)—and leads, therefore, to a more effective use of resources as compared to when this knowledge is not present, as in the "partly constrained" scenario. The combination of a diverse geography, a changing environment, and an awareness of such changes do create boom-and-bust like dynamics (albeit slightly less pronounced than in the other scenarios) on the global scale, but it shows much more complex and diverse population patterns on the local scale. These regional and rich differences indicate that single island-wide narratives of collapse are too simplistic and that observational inferences at the local scale cannot be reliably and directly extrapolated to the global scale.

The mathematical model presented here, and actually any other model of ancient human societies, however sophisticated, is a simplified representation of complex ecological and socio-economic issues. Our model constitutes an initial characterisation of the historical Rapa Nui society from environmentally realistic and agent explicit perspectives. This initial mathematical modelling treatment, although novel in relation to Easter Island (Merico 2017), has obvious limitations. However, the flexibility offered by this type of models allows for continuing developments and implementations (Bonabeau 2002). Avenues of future development may include a more elaborate social organisation of household agents. In our model, agents act independently from one another and are not governed by central organisations. Easter Island was divided into several clans run by chiefs that organised harvest activities, for example by limiting access to resources through taboos, *tapu* (Cauwe and Latsanopoulos 2011), and trading manufactured and harvested goods (e.g. Bahn and Flenley 2017). A clan with some political power would have access to resources in areas larger than the immediate surroundings considered in our model and in a coordinated manner. Exchange and distribution of resources across settlements could be a very interesting area of model development to understand, for example, the effects of different structures of trading networks to population size and the number and distribution of clans and communities, as recently demonstrated by the work of Chliaoutakis and Chalkiadakis (2020). The inclusion of additional resources like fishery, coastal freshwater seeps (DiNapoli et al. 2019), or diversified farming practices, including wetland agriculture (Rull 2020), also has the potential to produce valuable insights in relation to population dynamics. Complexity can also be added in relation to human behaviour, for example, by allowing continuing technological progress and capital accumulation typical of some pre-industrial societies (Tisdell and Svizzero 2015), despite the poverty and severe resource limitations imposed by the small size and isolation of Easter Island. A more advanced version of our model could allow agents to choose between cooperation and competition strategies, myopic and far-sighted behaviours, and to pass on the most successful strategy to following generations.

A growing body of research considers the effects of potential climatic perturbations on the Rapa Nui society (e.g. Rull 2020; Lima et al. 2020). The hypothesis that climatic variations may have affected population dynamics is based, for example, on the temporal correlation of drought periods and shifts of ceremonial centres (Cauwe and Latsanopoulos 2011), or on spatio-temporal patterns of forest density (Rull 2020). However, climate modelling (Junk and Claussen 2011) could not confirm the occurrence of climatic variations during Easter Island's late prehistory, and, more importantly, we have no clear information about how such climatic variations could have affected resources on the island. We include suggested periods of droughts of Rano Raraku (Rull 2020) in our model by making areas around this lake less attractive to agents during these periods but do not account for the consequences of such droughts on forest or soil fertility. In the sensitivity analysis, we show that while they influence regional population patterns, droughts have no noticeable effect on island-wide patterns. Future modelling studies may build up on our work to investigate how (heterogeneous) impacts of climatic perturbations affect resources and the population dynamics on regional and global levels.

Finally, while trees must have constituted a valued resource in particular for the firewood and the timber they provided (for building tools necessary for crucial activities such as agriculture, fishing, and statue carving), they were probably not essential for the survival of the society. The assumption that population growth depends on trees is not supported by clear and uncontroversial evidence. In particular, we know that the island was populated and, apparently, quite prosperously, according to some reports by the first European explorers (see, for example, Bahn and Flenley 2017) despite being entirely deforested. In this respect, a possible future improvement of our model could consider population growth independent from trees and rather treat this resource in the same way as we treated freshwater—easy access to trees in a location increases the attractiveness of that location.[1] Another uncertain assumption in our model involves the fact that even extremely low-yield cells are farmed despite some studies indicating that the amount of labour invested on agriculture by the productive population ranged between 10 and 20 person-hours per week on many small islands of the Pacific (Bayliss-Smith 1978). Our model assumptions lead to plausible spatio-temporal patterns, but this does not constitute a proof that such assumptions are correct. Different assumptions might lead to similar patterns or to results more consistent with a population that did not depend directly on the presence of a forest for survival. Given the uncertainties involved in the archaeological evidence, the aim of our study was not to pin down the exact patterns of deforestation and population growth, but rather to explore the impacts that people's knowledge and environmental heterogeneity might have exerted on such patterns.

5 Conclusions

The environment of Easter Island played an important role in limiting human growth. Despite its simplicity, our model provides valuable insights not only about this rather obvious relationship but also about how certain assumptions on human behaviour, specifically environmental knowledge in moving decisions, impact the dynamics of deforestation, population size, and land use at the local scale. A society, in which households are spatially restricted in their harvest, shows

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[1] We thank the anonymous reviewer for this suggestion.

population dynamics more in line with a typical collapse narrative. A society, in which households use environmental knowledge to decide on settlement locations, follows a pattern that is similar to a collapse but less pronounced. Ultimately, the continuous dependency of the agents on a dwindling and non-renewable forest is the primary driver of population declines in our scenarios (the cultivation of sweet potatoes is not limited by soil degradation by model design). However, the model produces stable population sizes when cultivation can fully replace the dependency on trees in an entirely deforested island, provided that soil degradation is not an issue for agricultural activities. The model shows that environmental knowledge, a factor that we presume must have characterised the Rapa Nui society, leads, on a regional scale, to complex and diverse population dynamics ranging from collapse to slow demise and even to continuous growth. We note that the form of knowledge implied by our assumptions is still tied to an exploitative behaviour and not, for example, to a sustainable behaviour. The important implications of our study are that an island-wide narrative of collapse is too simplistic given the variety of population patterns we found at a regional scale. We conclude, therefore, that global-island narratives might not be representative for regional dynamics and, in turn, observational evidence on a regional scale cannot be reliably extrapolated to the global scale.

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Chapter 17
Economic Causes and Consequences of Deforestation on Easter Island

James A. Brander

1 Introduction

One approach to understanding the deforestation of Easter Island is based on economic and ecological modeling (EEM) of the interaction between the forest stock and the human population. The objective of the EEM approach is to estimate and explain the temporal pattern of deforestation and of the human population on Easter Island using a mathematical model incorporating relevant economic and ecological principles.

An early EEM approach to Easter Island deforestation, developed by Brander and Taylor (1998) (BT from now on), is related to the "predator-prey" models originally proposed and analyzed by Lotka (1925) and Volterra (1926). As applied to Easter Island, the forest is the "prey" and the human population is the "predator." Predator–prey models may or may not give rise to a "boom-and-bust" pattern depending on parameter values—that is, depending on the precise relationships in the model. The BT model for Easter Island is consistent with a boom-and-bust pattern and identifies the key factors underlying this pattern.

This chapter provides an extension and modification of the BT model that allows for a more detailed and more accurate representation of Easter Island's economy and also incorporates new information that has emerged since the BT model was published in 1998. The result is a model that tracks the known information more accurately and more clearly identifies the important economic factors underlying Easter Island's deforestation and population rise and fall. This chapter also shows how alternative assumptions about important but uncertain factors, such as the extent of soil erosion, affect the estimated trajectories of population, deforestation,

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_17

and standard of living on the island. In addition, as a contribution to a book on multidisciplinary approaches to studying Easter Island, this chapter also describes the role of economic principles in understanding Easter Island's evolution.

This chapter is not the first extension of the BT model. Other valuable extensions and general contributions to the EEM approach include Anderies (2000), Basener and Ross (2004), Dalton and Coats (2000), Good and Reuveny (2006), and Pezzey and Anderies (2003) among others. This general line of research has been reviewed by Merico (2017).

Relative to this literature, the model developed here contains several significant innovations. First, the BT model, like many economic models, is a "two-sector" model in that it separates the economy into two components, a resource sector and a service sector that represents "everything else." The BT resource sector encompasses both the forest and the agricultural sector, and the underlying resource is referred to as a "forest-soil complex." This chapter uses a three-sector model in which the resource sector is sub-divided into a forestry sector and an agricultural sector and therefore allows a more detailed estimation of the forest stock trajectory.

In addition, the growth of the forest is represented by a generalization of the logistic model to include a "threshold level" of the forest stock below which it is not viable, and the production functions in both forestry and agriculture are generalized from a "Shaefer" form to a "Cobb-Douglas" form. These extensions and generalizations are possible because the current paper relies on numerical methods to solve the model, in contrast to BT, who sought to develop a model simple enough to allow for closed-form analytical solutions.

One motivation for using the economic-ecological modeling (EEM) approach is that it incorporates economic information and ecological information in a way that may yield insights not readily obtained using other approaches. For example, Brander and Taylor (1998) show that the interactive trajectory of a renewable resource stock and a typical pre-modern population in a closed system, such as Easter Island, would depend crucially on the "intrinsic growth rate" (or regeneration rate) of the resource stock. A relatively slow-growing resource stock naturally gives to a boom-and-bust pattern, whereas a sufficiently fast-growing resource would yield monotonic convergence to a steady state. The evidence suggests that the palm forest on Easter Island was composed primarily of the slow-growing *Jubaea chilensis* palm (Grau 2001) or a similar species, whereas other Polynesian islands, such as Tahiti, had much faster-growing palm species. Therefore, the EEM approach can explain not only why Easter Island had a boom-and-bust pattern of development, but can also explain why it differed from most other major Polynesian islands, which did not exhibit a boom-and-bust cycle.

Another important motivation for the EEM approach is that it allows the modeler to "fill in" the full dynamic trajectory of the resource based on fitting the model to a few known data points. In the case of Easter Island, it is known that most of the island was covered by a dense palm forest prior to colonization by Polynesians and that the forest was essentially gone by 1722 at the time of first European contact. In addition, significant information regarding the intervening period is available from sediment cores from several locations on the island. The EEM approach allows us to put together these pieces of information in a consistent way to estimate the overall temporal pattern of deforestation and human population dynamics.

Providing a meaningful EEM quantification of Easter Island (or any other environment) requires reasonably accurate information about important functional relationships between variables. For example, the assumed "production functions" that show the relationships between inputs such as labor and output such as forest products need to be reasonable approximations. Good estimates of specific parameter values are also needed. This includes information about the forest, the people, and the economy. If the functional relationships or parameter estimates are highly uncertain, then the accuracy of the model is also highly uncertain. However, the model can, at a minimum, show the implications of different plausible assumptions for the trajectory of population, the forest stock, and other key variables.

Sections 2 summarizes important information about the forest, Section 3 reviews demographic and other information about the Rapa Nui population on Easter Island, and Sect. 4 provides key facts about the economy. These sections also specify the proposed functional relationships in each of these areas. Section 5 describes the parameter values used in the base-case simulation and illustrates that simulation diagrammatically. Section 6 shows the effects of using different parameter values and different assumptions about the model. Section 7 discusses the major economic themes and principles in the analysis, and Sect. 8 contains concluding remarks.

2 The Easter Island Forest

Our knowledge of Easter Island's forest is due mainly to paleo-ecological studies of the pollen content of sediment cores taken from several locations on the island, first reported by Flenley and King (1984) and Dransfield et al. (1984). As emphasized by Rull (2020b), these core-based pollen studies are limited, consisting of cores taken from only three specific locations on the Island, Rano Raraku, Rano Aroi, and Rano Kao.

The three source locations for cores exhibit quite different temporal patterns, although virtual extinction of the palm forest by about 1600 CE is evident at all three sites. Based on Figure 7 in Rull (2020b, p. 133), the Rano Raraku cores exhibit a sharp deforestation pulse starting just before 1200 CE, followed by slow decline until another deforestation pulse starting about 1450 CE. The Rano Kao record indicates marked deforestation periods around 1050 CE and 1350 CE, with significant regeneration in the intervening period. The Rano Aroi record shows significant expansion of the forest between about 1400 CE and 1520 CE, after which deforestation begins. Thus, significant deforestation began at markedly different times at the three locations and deforestation pulses occurred at different times. And, most notably, two of the three sites experienced forest expansion over significant periods.

As these three locations account for only a small part of the island, it is far from clear what the overall temporal pattern of deforestation was, or when it began.

However, core sample evidence has been augmented by root imprints obtained by Andreas Mieth and Hans-Rudolf Bork and others, as described by Mieth and Bork (2017, Ch. 2, pp. 39–41). This includes obtaining root imprints in edges of gullies, corresponding to significant depth and therefore to considerable age, but without the need for drilling cores. This evidence suggests that about 75% of the island was covered by a dense palm forest of close to 20 million individual palm trees prior to colonization. Mieth and Bork (2017, p. 39) also assert that evidence for the Jubaea palm is "conclusive," although it may have been a variant of the Jubaea genus other than the *Jubaea chilensis*. These giant palms typically grow to a height of over 20 meters and a diameter on the order of 2 meters (Grau 2004).

In addition to the dominant palm species, the forest also included many other species of smaller trees and shrubs, most of which were also harvested to extinction well before first European contact. One shrub that survived was the Toromino shrub, which was apparently extinguished except for a single plant from which all known current cultivated specimens descend (Mieth and Bork 2017). The forest was also home to many species of land-based birds that also went extinct as their habitat disappeared.

There is a general agreement that the great majority of the deforestation occurred between 1250 CE and 1600 CE. This is sometimes taken to imply that first colonization occurred shortly before 1250 CE, However, as pointed out by Mieth and Bork (2017), this conclusion is implausible. First, the "great majority" is not the same as "all." Some significant deforestation occurred well before 1250 CE, and no later than about 1050 CE (Rano Kao). In view of the variety in deforestation times exhibited by the three well-studied locations, it is likely that other parts of the island had still different starting times for deforestation. Given the large number of other locations, it is therefore possible that some areas began significant deforestation before 1050 CE.

One further point about deforestation to be considered is the "rat hypothesis" advanced by Hunt (2007), that rats brought to Easter Island by Polynesians consumed or at least damaged the nuts of the palms and therefore prevented growth of new trees, converting the forest into a non-renewable resource. My reading of the evidence is against this hypothesis. First, as noted by Vogt and Moser (2010) and others, most of the preserved nutshells from Easter Island do not show gnawing marks, although a few do show damage, suggesting that the rats had only a small impact on the forest. Second, two of the three sources of cores exhibited significant periods of forest regeneration well after initial colonization of Easter Island. These observations seem to conclusively reject the hypothesis that rats stopped new forest growth. It is possible that rats might have slowed the regeneration rate slightly, and it is possible that drying on the island in the early colonization period, as indicated in Rull (2020b, Fig. 7), might have slowed regeneration, but my reading of the evidence is that these effects were likely of minor significance.

The model component used here to represent growth of the forest stock is the logistic model with a threshold, as described by the following forest growth equation:

$$G(F) = rF\,(1 - F/\mathrm{K})\,(1\text{–}M/F) \tag{17.1}$$

In this equation, G is the growth of the forest stock in a given period, F is the size of the stock at the beginning of the period, r is the intrinsic growth rate, K is the carrying capacity (maximum possible stock size), and M is the minimum viable stock. Initially, when $F = K$, the forest stock is at its maximum size and therefore the growth, $G(F)$, is zero, as with the standard logistic growth function.

If $M = 0$, then the forest growth equation reverts to the standard logistic form used in BT and in many other studies. If M is positive, and if the stock falls below M, growth is negative and the stock follows a path toward extinction. See Bascompte (2003) for a discussion of this growth equation and related approaches.

There are several reasons why M would exceed zero. One reason is soil erosion. A large stand of trees provides a windbreak and retains water and soil through its root system. If most of the stand is cleared, beyond some point topsoil is readily lost from wind erosion and from runoff when rains occur. Depending on conditions, erosion could render such small isolated stands unsustainable.

A second reason relates to the loss of an "insurance" effect as the stock gets small. A large forest can survive localized disasters such as lightning, localized fires, a localized temporary drought, sabotage of trees due to internecine human conflict, other human error, disease, etc., as losses in one area can ultimately by replaced by expansion of healthy stands of trees elsewhere. But a stock that is reduced to just a few small stands is just a few small localized negative shocks away from an extinction path.

3 Easter Island's Human Population

Easter Island's indigenous human population, the Rapa Nui, was Polynesian in origin. As reported in Rull (2020a, Ch. 2, p. 59), some DNA studies of modern indigenous Rapa Nui indicate a contribution of about 8% of the genome from Native Americans dating from somewhere between 1280 CE and 1495 CE. However, gene-based research by Fehren-Schmitz et al. (2017) finds no evidence of any Native American contribution predating first European contact with Easter Island. The Native American contribution, if there is one, may have arisen due to Native Americans being brought from South America to Easter Island by Rapa Nui sailors or by other Polynesians, or from independent Native American contact with the island after the Rapa Nui were well-established.

One unresolved question about Easter Island is the date of first Polynesian colonization. Early study of Easter Island suggested a date as early as 400 CE.

However, at present the (rather broad) range of 800 CE to 1200 CE suggested by Flenley and Bahn (2003) is widely accepted.

Some observers, particularly Wilmshurst et al. (2011) suggest an even later date based on carbon dating of artifacts (and assert relatively late colonization dates for much of Polynesia). However, Mulrooney et al. (2011) note a number of flaws and some outright errors in this work that bias the implied date of colonization upward (later in time). Furthermore, as pointed out by multiple authors, the date when the population was sufficiently large and sufficiently established to leave a significant number of artifacts is very likely later than the date of first colonization, possibly much later. Carbon dating is not precise but, even assuming that we have accurate carbon dating of some artifacts, that date is an upper bound on first colonization, not a "best estimate" of when colonization first occurred. It is likely that initial colonization was by a small group of perhaps 50 to 100 individuals, arriving on one to three ocean-going canoes traveling together (See, for example, Martinsson-Wallin and Crockford (2001)). Given the broad dispersion of artifacts and other indicators of human population dating from the late 1200s CE onward, it is unlikely that a small initial group arriving only two or three generations earlier (assuming about 20 to 25 years per generation) could have grown sufficiently quickly.

In addition, the pattern of deforestation is itself important evidence and, as noted in Sect. 2, there is evidence of significant deforestation by about 1050 CE. It is sometimes suggested that such deforestation could be the result of natural causes such as climate change or disease, but climate change on Easter Island was mild over this period and, if climate change such as general drying or general cooling was the explanation, then it should have affected all parts of Easter Island, not just Rano Kao. And, while climate change might have slowed forest regeneration, it would be unlikely to cause actual deforestation over the relevant time horizon. Similarly, while plant disease or parasites are possible, there is no actual evidence to support this possibility. It would be a remarkable coincidence if such natural deforestation just happened to occur at the same time when other evidence, plausibly interpreted, suggests contemporaneous human colonization.

If significant human-based deforestation was occurring by about 1050 CE, the implied date of first colonization would be no later than 1050 CE. I take 1050 CE as the starting point of human colonization, although the correct date could well be earlier. Moving the date of first arrival back in time by 50 years or so would not affect the qualitative nature of model, as everything would just be moved 50 years (or more) earlier and the resulting forest stock and population trajectories would still be generally consistent with known evidence. If the date of first arrival was even earlier, that would imply lower (but still plausible) natural fertility than I assume in the base case in this chapter.

Based on Polynesian demographic patterns as described by Kirch and Rallu (2007) and the recent study of New Zealand by Brown and Crema (2019)), an early population growth rate of 3% per year would be a very high estimate. Even 2% to 2.5% per year would be high, although plausible if the ratio of resources to population is high and life is neither difficult nor dangerous. Kirch and Rallu (2007) state that the long run average population growth rate in most of Polynesia was probably less than 1% per year. My model allows for a maximum possible population growth rate of 2.5% but fertility falls and mortality rises in response to declines in per capita food availability.

The base model uses the following fertility and mortality functions.

$$br = b_1 \left(1 - \frac{b_2 L}{C}\right) \tag{17.2}$$

$$mr = m_1 \left(1 + \frac{m_2 L}{C}\right) \tag{17.3}$$

In these equations, L is the human population, C is consumption of food and other goods that contribute to fertility and survival. The model assumes that $C = H + Q$, the sum of agricultural output and forest output. The other sector (the "everything else" sector) consists largely of statue carving and movement and associated religious functions that do not contribute directly to nutrition and other basic physical needs. The demographic parameters are b_1, b_2, m_1, and m_2, all of which are taken to be positive. Like BT and much of the literature on pre-industrial demography (such as Fernihough 2013; Klemp and Møller 2016) these functions assume that fertility and mortality are linearly related to some measure of either real income or its inverse (L/C in this case).

If the food supply is very large relative to population, then the birth rate, br, is b_1 and the mortality rate, mr, is m_1. In this situation, the overall population growth rate, $pr = br - mr = b_1 - m_1$, would be at its maximum level. As population L rises relative to food supply F, the birth rate falls and the mortality rate rises (given that parameters b_2 and m_2 are positive), reflecting a Malthusian structure.

The most striking feature of the Rapa Nui society was the creation of large statues or "*moai*." These statues were carved from the Rano Raraku quarry and moved to various locations on the island. Creation of statues is related to the question of deforestation as it is very likely that wood from the forest was used to create rollers or sleds on which statues could be moved (Van Tilburg 1996). The forest was also a source of material for implements such as levers that would have been necessary for moving and positioning statues. Various time periods have been suggested for the start of *moai* carving, with the earliest being some time shortly before 1200 CE. The end period was probably between about 1625 CE and 1650 CE, although both earlier and later times have been suggested.

The other main cultural point to note is the dramatic social shift from the ancestor worship centered on the moai to the Birdman cult. The dates of the Birdman cult are also uncertain but carbon dating and other evidence described by Robinson and Stevenson (2017) strongly suggests Birdman cult activity in the early 1600s.

4 The Economy of Easter Island

The forest sector had a variety of outputs although, for modeling purposes, all forest output is aggregated into a single category. One very important use of the forest would have been to harvest trees (other than palms) to make canoes and other sea craft that could be used for fishing. Therefore, fish is one important output of the forest. In addition, the forest was home to various species of land-based birds that would also have contributed to the food supply. It has also been suggested that the Rapa Nui might have taken sap from harvested trees for drinking (Mieth and Bork 2017, p. 48). Thus, the forest would have contributed significantly to food production.

In addition, wood from the forest was used to build dwellings and for various tools and implements, including rollers for moving statues. Wood was also used for fires for cooking and for other purposes, although much of that wood for cooking would have come from other (smaller) tree species and undergrowth on the island, as implied by the analysis of charcoal remains.

4.1 Production Functions

Production in both the forest sector and the agricultural sector is modeled using Cobb–Douglas production functions, as is common in economic analysis. Also, agricultural output in pre-industrial societies is typically taken to exhibit constant returns to scale in labor and land as in, for example, Klemp and Møller (2016). The agricultural production function is

$$Q = \alpha L_a^q A^{(1-q)} \tag{17.4}$$

where Q is agricultural output, α is a productivity parameter, L_a is agricultural labor, and A is agricultural land. The exponents q and $1 - q$ are "elasticities." Each elasticity shows (approximately) the percentage increase in output if the associated input (labor or land) increases by one percent, holding the other input constant. It follows that if the elasticities sum to one, as assumed in this case, the production function has constant returns to scale, which implies that there is no particular advantage or disadvantage to greater scale: Doubling both inputs would double output. However, the marginal product of labor is declining in that, if we hold agricultural land fixed, the extra output obtained by adding more labor declines as the labor input increases.

In the forest sector, the production function is

$$H = \beta L_f^h F \tag{17.5}$$

where H (for "harvest") is forest output, β is a productivity parameter, L_f is labor used in forestry, and F is the forest stock. This production function is similar to the Shaefer production function used in BT except that the labor input has an exponent or elasticity, h, that is assumed to be less than one, which implies diminishing (instead of constant) marginal productivity of labor and is more realistic. This production function overall exhibits increasing returns to scale in that proportionate increases in labor and the forest stock would increase output more than proportionately. It is important to emphasize that the "forest sector" is taken to include the entire "downstream" output of forestry. In particularly, cutting down trees, making canoes and going fishing, and building dwellings from wood are all part of "forestry output" in this structure. Increasing returns to scale (advantages of scale) in forestry are plausible for several reasons, including the advantages of greater specialization at greater scale.

The forest sector competes with the agricultural sector for land. In the island's initial state at first colonization, most of the land was covered by the palm forest. Units of land can be defined such that the initial forest stock, K, is the same as the initial land area occupied by the palm forest, which is therefore also K. Some of the land, while unsuitable for palms, would have been available for agriculture, and some land was suitable for neither a palm forest nor for agriculture. I denote the initial agricultural land as A_0. It follows that the total amount of land usable for forestry and agriculture is $A_0 + K$. As time goes on, the forest stock is depleted and agricultural land increases accordingly, but the total amount of useable land does not change. Therefore, at any given time, the combined agricultural land, A, and forest stock, F, equals the amount of land available, $A_0, + K$ as expressed in Eq. 17.6.

$$A + F = A_0 + K \tag{17.6}$$

An interesting interaction between the agricultural and forest sectors is that burning of the forest cover would, in the short run, fertilize the soil and increase agricultural productivity, causing α in eq. (17.4) to increase. Even if most of the wood were used for other purposes, the roots and undergrowth would still be burned and there would be some other harvesting residue, creating some fertilizer effect. However, over time the loss of forest cover would lead to increased soil erosion that would gradually have a negative effect on agriculture, causing α to fall (See Zheng (2006) for an example of the dramatic increase in soil erosion caused by deforestation). These two effects are incorporated in the model through the following equation:

$$\alpha_t = \alpha_0 + \frac{zH_{t-1}}{A_t} - eA_t/K \tag{17.7}$$

The subscript t denotes time, α_0 is the initial productivity parameter, z shows the increase in short run productivity caused by last year's forest removal, H, and e shows the negative effect due to soil erosion as agricultural land, A, increases and deforestation therefore occurs. If we wish to ignore these two effects, we can set z and e to zero.

In addition to forestry and agricultural sectors, the model allows for a third sector that represents "everything else." This sector includes statue carving and various services including religious, domestic, governance, and security (military) services. This is a constant returns to scale sector in which the only scarce input is labor. Output V (for "ser*v*ices") is given by

$$V = vL_v \tag{17.8}$$

where v is a productivity parameter and L_s is labor used in this sector.

4.2 Demand, Utility, and Well-being on Easter Island

As with any economy, one important component of the Easter Island economy is the structure of preferences and demands (or "wants and needs") for different products. Economists often start by specifying a utility function from which demand functions can be derived. In that case, the utility function can also be used as a measure of well-being as higher values of the utility function reflect greater success in fulfilling the wants and needs of the population. BT use a Cobb–Douglas utility function. The model in this chapter uses a quadratic utility function, which is the other commonly used utility function and which is better if complete loss of one sector is possible, as is true of the forestry sector in this case. Specifically, the utility function has the following form.

$$U = u_1 Q - \frac{1}{2}u_2 Q^2 + u_3 H - \frac{1}{2}u_4 H^2 + V \tag{17.9}$$

where $u_1, \ldots, u_4$ are utility function parameters. This utility function is quadratic in Q (agricultural output) and F (forestry output) and linear in the service sector output. The service sector acts as a residual sector that provides a product with constant marginal value. It is therefore convenient to treat the service sector good as a numeraire good whose "price" is normalized to be one and the prices of the other two goods are the rates at which they can be exchanged for the service good. It follows from (9) that the demand functions for forest output and agricultural output are linear functions of their prices.

4.3 Allocating Labor

One important aspect of Easter Island's economy (or any other economy) is the system that allocates labor to different tasks. The most common assumption is that workers flow to the occupation where the value of their current marginal product is highest. The marginal product is approximately the extra output obtained by adding one unit of labor (one worker) to the production process. More formally, the marginal product is the derivative of the production function with respect to labor. Thus, for example, the marginal product of labor in forestry is $\mathrm{d}H/\mathrm{d}L_f = \beta h {L_f}^{(h-1)}F$. The value of marginal product in forestry is this marginal product multiplied by the price of forestry output. The value of marginal product in agriculture is derived in the same way. The value of marginal product in the service sector is always v.

The assumption that workers flow to the sector with the highest marginal product makes sense if workers themselves are able to keep the value of what they produce (their value of marginal product). It would also be expected in a system where someone else, such as a clan chief, makes the labor allocation decision and receives a share of the worker's value of marginal product.

If the value of marginal product is the same in all sectors, the labor market is in equilibrium. If not, adjustment occurs. Workers would leave sectors with a low value of marginal product and move to higher productivity sectors. This process would continue until an equilibrium was reached in which the value of marginal product is equalized across all sectors. Such adjustment may be fast or slow.

One aspect of the forest sector is that adding workers depletes the resource more quickly and reduces future productivity for all workers. This is a negative externality. An individual worker will work in forestry if the current value of marginal product is high. The externality is that when a worker decides where to work, that worker does not consider the costs (external effects) imposed on future workers in the form of reduced future productivity. In contrast, if a far-sighted manager controls access to the forest, that manager will limit access to the resource to prevent such over-harvesting. In the model, the agricultural sector is not subject to this dynamic negative externality. In practice, any such externality in agriculture is small relative to the forestry externality. The service sector is also not subject to any such negative externalities as it does not make use of any underlying resource base.

BT assume instantaneous labor market adjustment and an open-access forestry sector, leading to over-harvesting and ultimate depletion of the resource. This chapter uses a similar approach, assuming that the forest is an open-access resource and that, at any given time, workers flow to the sector where the value of marginal product is highest. However, this chapter assumes a more realistic adjustment process rather than instantaneous adjustment. Specifically, all new workers entering the labor force enter the sector with the highest marginal product of labor at that time, but old workers in other sectors remain in those sectors and the labor forces in those sectors decline only as old workers retire or die.

5 Parameterizing and Simulating the Base Model

The model consists of eqs. (17.1) through (17.9) and is dynamic in the sense that variables evolve over time. The model starts at the time of first colonization of Easter Island by Polynesians and each variable is at its initial value. The initial harvest is determined by production function (5), with the forest stock equal to its initial carrying capacity, K. Growth in the forest stock occurs according to growth function (1), although growth in the first period is zero because $F = K$ initially. In the next period, the forest stock equals the initial stock minus the prior harvest and in later periods the forest stock equals the previous stock minus the difference between the harvest and forest growth. Therefore, the harvest will change from year to year, as will other variables. The model uses discrete time periods (of one year) rather than continuous time and is therefore a difference equation model rather than a differential equation model as in BT, but that change has no substantive effect.

The objective of the modeling exercise is to choose parameter values and starting values of variables that are realistic and that generate a dynamic pattern consistent with known facts. This approach is an example of the dynamic "computable general equilibrium" (CGE) method, although most CGE models are much more complicated. There are enough parameters to provide considerable flexibility in fitting the model to known data. Even so, it is not necessarily true that any set of plausible parameter values and initial values can capture known facts. Such a situation would imply that one or more assumed functional relationships is not a good enough approximation to reality. In this case, however, the model can replicate known facts well.

All parameters have to be assigned values. Those parameters, such as the intrinsic growth rate, r, or the fertility parameters do not change over time. Variables do vary over time. For example, the actual growth of the forest in any year is calculated within the model and varies over time. Some of the variables need to be assigned starting values. For example, the initial population must be specified. In all years after the first, the population is determined by the model. Some variables are calculated by the model in the first year and all subsequent years, such as the first-year agricultural output or the first-year birth rate. Table 17.1 shows the parameters, any variables that require estimated starting values, and most of the other variables of interest.

The parameters and initial sources are derived in several ways. First, some parameters are just a matter of scaling. I have set the initial forest stock (and the carrying capacity) at 20,000 in view of estimate of Mieth and Bork (2017) of about 20 million palm trees (so one unit of forest stock represents about 1000 trees) and because that is a convenient scale for diagrams. However, it could have been scaled to any value (such as 100), although that scaling would have to be consistent with the scaling of other variables, such as the productivity parameter and agricultural land.

Some parameters are taken from outside sources. In particular, the demographic parameters are based on my reading of Kirch and Rallu (2007) and other sources.

Table 17.1 Parameters and variables

Parameter	Name	Value	Variable	Name	Initial value
b_1, b_2	fertility parameters	0.035, 0.01	A	agric. land	1000
β	forestry productivity	0.00002	α	agric. productivity	0.012
e	erosion parameter	0.005	br	birth rate	cm[a]
h	forestry elasticity	0.8	F	forest stock	20,000
K	forest carrying cap.	20,000	G	forest growth	cm
m_1, m_2	mortality parameters	0.01, 0.01	H	forest harvest	cm
M	min. viable forest stock	2000	L	population	50
q	agriculture elasticity	0.5	mr	mortality rate	cm
r	intrinsic growth rate	0.004	Q	agricultural output	cm
$u_1, \ldots, u_4$	demand parameters	100, 1200, 2	S	service output	cm
z	fertilizer parameter	1.0	U	utility	cm

[a] cm = calculated by the model. This table shows the parameters values used in the base-case model along with the required initial values for some variables

The initial amount of agricultural land is taken to be 1000, reflecting the finding of Mieth and Bork (2017) that the forest covered about 75% of the island. The remaining 25% must have been unsuitable for forest growth and most of it would, presumably, also be unsuitable for agriculture mainly due to basalt outcrops. However, some land would have been suitable for agriculture even though it was not suitable for palm trees. The value of 1000 is 5% of the initial forest stock and therefore 5% of the initial land devoted to the forest.

The initial population is taken to be 50, and the model makes no distinction between the population and the labor force. That is, the model does not include a population category corresponding to young children who cannot work. If we were to introduce such a category, we would just allow the population to exceed the labor force by some percentage to account for those children and the model would be otherwise unaffected.

The value of the intrinsic growth rate (0.004) is taken from BT and the sources cited there. This means that the forest stock would expand at the rate of about 0.4% per year or about 4% per decade. This is slow growth, as is characteristic of the Jubaea palm. The agricultural elasticities are typical for estimates obtained for pre-industrial agricultural production functions. The other parameters, particularly the productivity parameters and the forest elasticity parameter, are chosen to make the model fit the known data, subject to plausibility.

Some of the parameters and initial values do not have important effects in the sense that they can be changed substantially without having much impact on the model trajectories. For example, the assumed initial stock of agricultural land is in this category. Whether the initial value is 500 or 2000 (instead of 1000) has little impact. The fertilizer effect and erosion effect also do not have much impact at the levels I have assumed and the model is similar if those effects are eliminated, but they do have some impact that is worth noting. The size of the initial population also does not have much impact (within the reasonable range).

The minimum viable forest stock is taken to be 2000, which is 10% of the initial stock. This is a fairly high value. But this variable also is not particularly important in that the qualitative behavior of model is not affected much if different choices are made. A low value of 500 or even 0 has little effect on the overall trajectory of the main variables, except that the forest stock does not go fully extinct but stabilizes at a low level.

The most important parameters are, as is consistent with BT and other EEM work in this area, the demographic parameters and the intrinsic growth rate. Those parameters determine the basic character of the model. The production function parameters are also important. Changing these parameters by modest amounts can change the qualitative behavior of the model, as illustrated in the next section. Figure 17.1 shows the base-case simulation of the model, using the values shown in Table 17.1.

The simulation in Fig. 17.1 tracks known facts about Easter Island reasonably well. In particular, the period of rapid deforestation (about 1150 CE to about 1450 CE) followed by extinction of the forest shortly after 1600 captures the path of deforestation. The population peak is somewhat lower than in BT but, at close to 7000, is still much higher than the estimated population of between 2000 and 3000 at first European contact. However, the decline in per capita utility or well-being is much sharper than the decline in population.

This decline in per capita utility or well-being reflects basic economic principles. In the absence of epidemics (which were almost certainly absent from Easter Island before European contact), conditions have to become very difficult to induce a decline in population. Without getting into a discussion of whether the Rapa Nui suffered a "collapse" or merely a "decline," the model implies a very steep drop in standard of living. This sharp decline is consistent with other economic evidence,

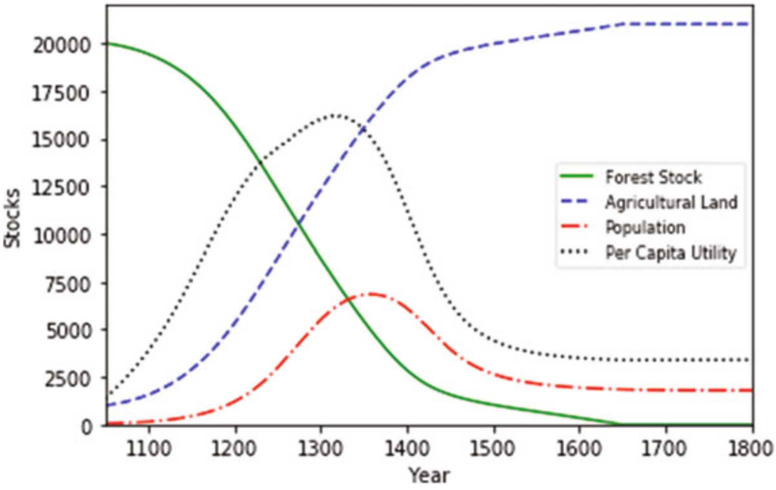

Fig. 17.1 Easter Island simulation base case

such as the use of stone chicken houses, which implies a high level of concern about security and is indicative of a serious decline in economic fortunes. I also note the frequency of an implement that might be regarded as a weapon (the "mata'a") in the archeological record during the period of decline, although some scholars argue that the mata'a is just a tool with many possible uses.

6 Alternatives

One value of the model is that it allows experimentation with alternative parameter values. This section provides four alternatives or "scenarios" that illustrate which aspects of Easter Island were of major significance and which had only minor effects. The first scenario eliminates the minimum viable stock consideration, the fertilizer effect of harvesting, and the erosion effect of lost forest cover. Figure 17.2 shows the effects.

Figure 17.2 is not very different from Fig. 17.1, indicating that the minimum viable stock constraint, the fertilizer effect, and the soil erosion effect do not change the basic character of how Easter Island evolved. Nevertheless, there are meaningful differences between Figs. 17.1 and 17.2. Most importantly, long-run sustainable per capita well-being ("utility") is substantially higher after Year 1500 in Fig. 17.2. The most important reason for this is eliminating the soil erosion effect. In other words, the base model implies that soil erosion due to lost forest cover had a significant negative impact on long-run well-being on the island, even though the overall dynamic pattern of the major variables is similar in both figures. My reading of the evidence suggests that soil erosion is important enough that it should

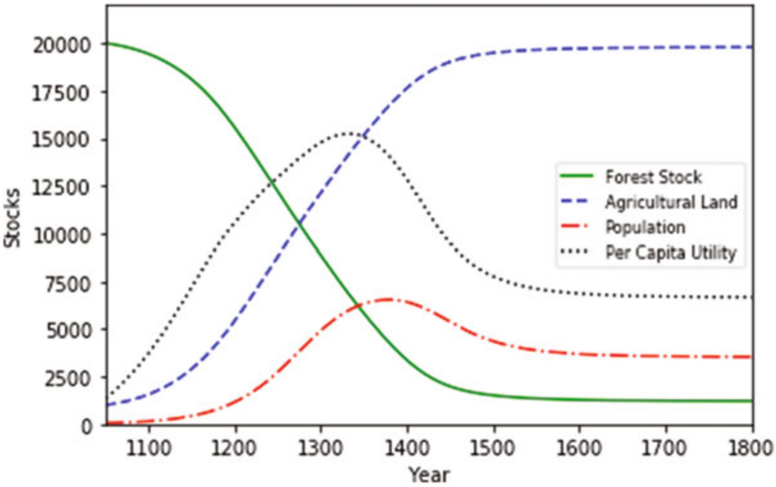

Fig. 17.2 Effect of eliminating minimum viable stock, erosion, and fertilizer effects

be included in the model. Some scholars have suggested that soil erosion was a localized phenomenon and not significant in coastal regions.

The second major difference is that, in Fig. 17.2, the forest stock is never completely extinguished, although it is reduced to less than 10% of its original size. This effect is due to dropping the minimum viable stock feature. Without this feature, when the forest is very small, it grows faster than when it is larger. In addition, the trees are sufficiently dispersed and, presumably, inferior in quality, that the cost of harvesting the last few trees is high enough to prevent complete extinction. This may be unrealistic and is one reason for including the minimum viable stock feature of the model.

The second alternative scenario to consider is an alternative considered by BT. As noted by multiple authors, the Jubaea palm is very slow-growing. The assumed base-case intrinsic growth rate of 0.4% per year is taken from Brander and Taylor (1998), who calculated this estimate based on horticultural information on the Jubaea palm. However, we can estimate what would have happened if the intrinsic growth rate of the palm forest had been similar to the coconut palms on Tahiti, about 3.5% per year (instead of 0.4% per year). Figure 17.3 shows the results of keeping all the base-case parameter values except for this one change.

This scenario is not intended to represent a realistic possibility for Easter Island, as the assumed intrinsic growth rate is much too high. The scenario is intended to show the importance of the intrinsic growth rate in explaining the difference between Easter Island and other Polynesian islands. As in BT, this alternative completely changes the character of the model's trajectory. The boom-and-bust cycle disappears, per capita utility is much higher, and both population and the forest stock converge on a steady state. It is no surprise that, other things equal, an economy is much better off with a fast-growing resource than with a slow-

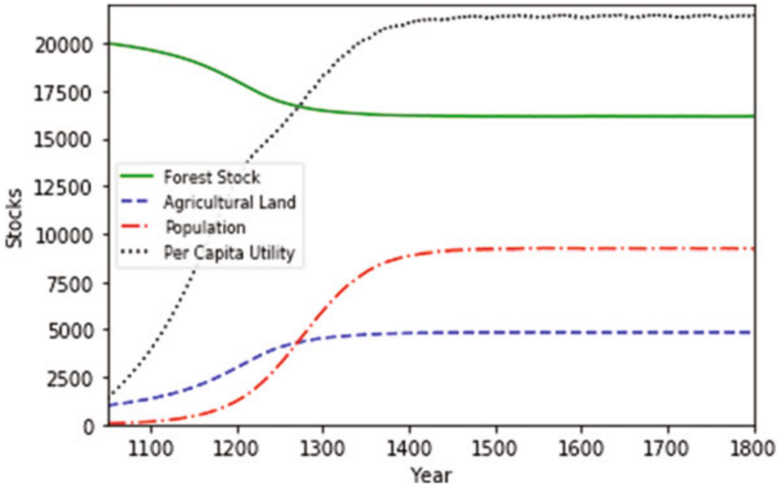

Fig. 17.3 Fast forest growth

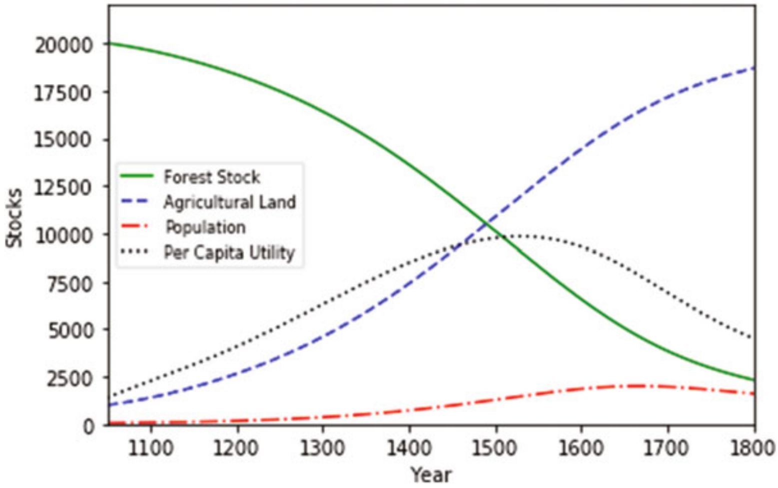

Fig. 17.4 The effect of a lower maximum birth rate

growing resource. The more surprising finding is that the dynamic adjustment on the model is completely transformed even though underlying preferences and behavioral assumptions are unchanged.

Figure 17.4 illustrates the effect of alternative demographic assumptions. Figure 17.4 has the same parameter values as Fig. 17.1 except that the demographic parameters are adjusted so that the maximum possible population growth rate falls from 2.5% to 1.5%.

Reducing the maximum birth rate has the natural effect of slowing down but not eliminating depletion of the forest and expansion of agriculture. In addition, the overall boom-and-bust pattern, while still present, is muted as the maximum population is much lower and the long-run level of per capita utility is significantly higher. Some scholars view a trajectory of this type as being a good representation of the current understanding of the actual trajectory of Easter Island.

The final alternative to consider is the "optimal management" scenario. This scenario asks what would have happened if the forest had been optimally managed instead of being subject to open access. The specific policy rule considered is as follows. The model proceeds exactly as in the base case up to the time when the forest stock is reduced to the size that provides the maximum sustainable yield, which occurs where forest growth per year is maximized. (This maximum yield forest stock is much less than the carrying capacity, where the annual growth of the stock is zero.) At this time, the labor force in forestry is reduced to the level that would generate the maximum sustainable yield from forestry. This requires a significant reduction in the forestry labor force to prevent further depletion of the forest and therefore lowers per capita income sharply at that point. Net fertility also falls sharply due to the decline in forest output. However, per capita utility and population reach a steady state soon after and remain at that level.

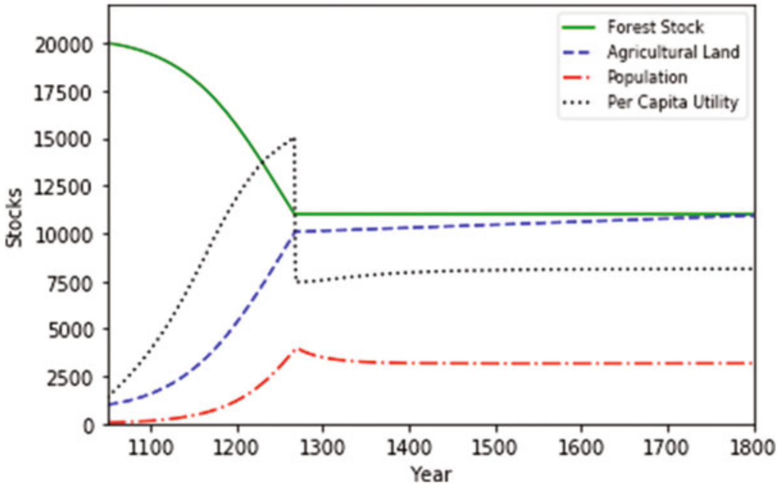

Fig. 17.5 Optimal management of the resource

Figure 17.5 shows that this path provides the highest possible steady state per capita utility given the low underlying intrinsic forest growth rate of 0.004 (0.4%) per year. This is not nearly as good as having a faster-growing resource (as in Fig. 17.3) but it provides a much better long-run outcome than the base case as measured by per capita utility.

7 Economic Principles and Easter Island

This section reviews two major economic themes in the analysis. First, economic analysis focuses on individual economic incentives—the desire to enjoy as high a standard of living as possible. In many pre-industrial situations, for the majority of people this amounts to trying to obtain enough food and other basic necessities on a day-to-day or year-to-year basis to stay alive. Reproductive incentives, which may support longer term well-being if children are expected to make net contributions to family welfare, are also very important.

So how would basic economic incentives explain the large investment in food and labor required to build and transport the moai? There are two possible answers. First, it is possible that people placed high value on such statues—that they obtained utility or well-being from the creation or existence of the moai. Second, a more likely explanation is that labor allocation decisions may have been made largely by leaders who perceived status or other benefits from maoi production and who therefore had incentives to promote high levels of such activity.

Individual incentives may act in the collective interest, which is the main theme in Adam Smith's foundational 1776 treatise, the "Wealth of Nations." But sometimes individual incentives do not serve the collective interest. Open-access resources provide one such counterexample, as first clearly shown in a formal model by Gordon (1954). In the Easter Island model, decisions made by individual workers or others controlling them leads to over-harvesting of the forest stock that ultimately reduces per capita well-being on the island. In addition, individual incentives regarding fertility lead to population growth at a level that also contributes to resource depletion and a reduction in per capita well-being, consistent with the classic work of Malthus (1798).

Over-harvesting due to individual economic incentives is a property of the model that may or may not closely reflect actual behavior on Easter Island. Possibly non-economic factors are of more relevance. But economics emphasizes the possible role of open-access resources and of underlying economic demography.

A second economic theme implicit in this chapter is the importance of economic and ecological fundamentals in explaining differences between societies. If we want to compare Easter Island with Tahiti, economists would not attribute the dramatically different outcomes to differences in motivation, in sensitivity to the environment, in social custom, or in ethical, moral, or religious belief. Such things might be important, but economists would start by considering economic and ecological differences. In the case of Easter Island and Tahiti, the difference in the intrinsic growth rates of the different palm forests on the two islands is an economically satisfying explanation that does not rely on unexplained differences in social organization or social custom.

Economists of course recognize that cultural institutions and economic fundamentals interact in a complex system of co-evolution. However, to a first approximation, economists are likely to view unusual or unique aspects of the culture on Easter Island as consequences of Easter Island's underlying economic fundamentals rather than as causes of economic phenomena. For example, the elaboration of the ancestor worship and moai manufacture was largely due to the existence of suitable resources for carving and moving the statures and to the wealth derived from an abundant forest resource that allowed a fairly large share of labor force to be diverted into an activity (statue construction and movement) that did not contribute directly to food production. When the resources needed to move the statues became scarce and the level of wealth in the society fell, the emphasis on moai ended and a new dominant culture (the "Birdman" culture) was more reflective of a poorer and more competitive society.

8 Concluding Remarks

The modern understanding of Easter Island's pre-history changed dramatically when examination of sediment cores, first reported in by Dransfield et al. (1984), Flenley and King (1984), and a few others, became possible. Although deforestation had previously been speculated, suddenly deforestation became accepted fact and the story of Easter Island become one of ecological catastrophe as popularized by Diamond (2005), among others.

In recent years, there has been some resistance to the ecological catastrophe description. Rull (2020a, Chap. 11 this volume) reports that, although there is no doubt that nearly complete deforestation occurred prior to European contact, several papers have questioned whether a corresponding cultural and demographic crisis occurred.

The EEM model presented in this chapter is consistent with a dramatic decline in well-being on Easter Island well before first European contact. The basic economic logic contained in the equations of the model runs as follows.

Easter Island was colonized by a small group about or before 1050 CE. The group was too small to fully realize economies of scale (due largely to the inability to get the full benefits of specialization). However, the island was still very hospitable and population grew rapidly, probably at close to 2% per year, doubling every 30 to 40 years, for about 200 years, implying a population of about 3000 or more by 1250 CE and still growing fairly rapidly.

In this early period, the output of forest was very important in providing food, although there was some agricultural activity. The equations of the model do not specify that this output was fish, but the natural interpretation is that trees from the forest were used to create canoes and other craft that could be used for fishing. Initially, fishing and forest birds would have much more important sources of protein than the limited alternatives available from agriculture, although the Rapa Nui did bring chickens with them to Easter Island.

During this period, per capita living standards rose as the Rapa Nui obtained the benefits of economies of scale in forest-related activities and developed specialized skills. Wealth increased to the point where the society was able to support a large class of service workers. The model does not specify the nature of this service activity but we understand that a significant part of it consisted of building and moving statues and the associated religious and organizational activity.

Initially, forest depletion was slow and the forest would have seemed like an inexhaustible resource, but the pace of deforestation increased to the point where most of the forest had gone by about 1400 CE. The forest resource was replaced by agricultural land and the model allows a short run beneficial effect on agricultural productivity due to fertilization from tree harvesting residue, but this is more than offset in the long run due to increased soil erosion arising from loss of forest cover. Also, agriculture is taken to be a constant returns to scale activity that displaces an increasing returns activity (forestry), which has a negative effect on per capita productivity and per capita well-being.

The decline in per capita availability of food and other resources increases mortality and reduces fertility in a standard Malthusian pattern. The model does not specify to what extent the increase in mortality is due to declining nutrition directly and to what extent it reflects violent internecine conflict, but either is consistent with the model. Population peaks at just under 7000 shortly before 1400 CE, after which population growth turns negative. Ultimately, as the forest was extinguished, *moai* carving stopped and agriculture took up most of the available land. Population and per capita well-being stabilized at the relatively low levels observed by Europeans at first contact.

This description is the way the model works, not necessarily what actually happened but, as documented throughout the paper, this pattern is consistent with the empirical evidence. The decline of population, living standards, and *moai*-carving activity is perhaps too slow to be called a “catastrophe,” but it is certainly a dramatic decline.

In modern terms, it is as if Europe or the United States lost more than half its population over the space of a few generations and had real incomes fall to pre-WWII depression era levels. The key difference between Easter Island and the modern world is the role of technological progress. The model contains economies of scale but abstracts from technological progress although some technological progress did occur, such as the development of the rock garden. Incorporating a small amount of technological progress would not affect the general properties of the model. If the modern world is to avoid a comparable ecologically-based decline, the combination of technological progress and a demographic transition to sustainably low fertility will likely be the main reasons.

Acknowledgement I thank Barbara Spencer and Christopher Stevenson for very helpful comments.

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Chapter 18
Palm Forest to Gardens and Grassland: A Study of Environmental and Geomorphological Changes of the Te Niu, Rapa Nui Landscape

Joan A. Wozniak

1 Introduction

A series of Pleistocene volcanic eruptions and subsequent lava flows originating from Maunga Terevaka (Baker et al. 1974; Gonzalez-Ferran et al. 2004) formed the landscape of the northwest coast of Rapa Nui. Numerous lava flows are visible as layers of basalt on the 100-meter-high cliff face of the northwest coast. Paleosols were observed between some of these basalt layers. The presence of paleosols suggests that plants took root in the sediments and gravels derived from the weathering lavas. The most notable plant on Rapa Nui was a palm resembling the Chilean wine palm (*Jubaea chilensis*). The palm has been classified as *Phascalococcos disperta.* Its extinction occurred after the arrival of Polynesians on the island. This extinction has become symbolic of how humans can change their environment as a means to establish new environs, and at times to their own detriment (Diamond 2005).

Evidence of environmental changes that occurred on the northwest coast of Rapa Nui at Te Niu during the Holocene is presented and discussed in this chapter. The goal of this study was to understand the causes and processes of the ecological changes on an isolated, palm-covered island after people arrived there. To do this the Te Niu project area was set up on the steeply sloped western flanks of Maunga Terevaka. The Te Niu project area (500 m by 1600 m) extended from the western sea cliff to 1600 meters inland, between 100 m and 350 m elevation, as shown on the map illustrated in Fig. 18.1.

Early explorers from Europe, beginning in the early eighteenth century, documented the vegetation on the island upon their arrival. Roggeveen (1908) first

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_18

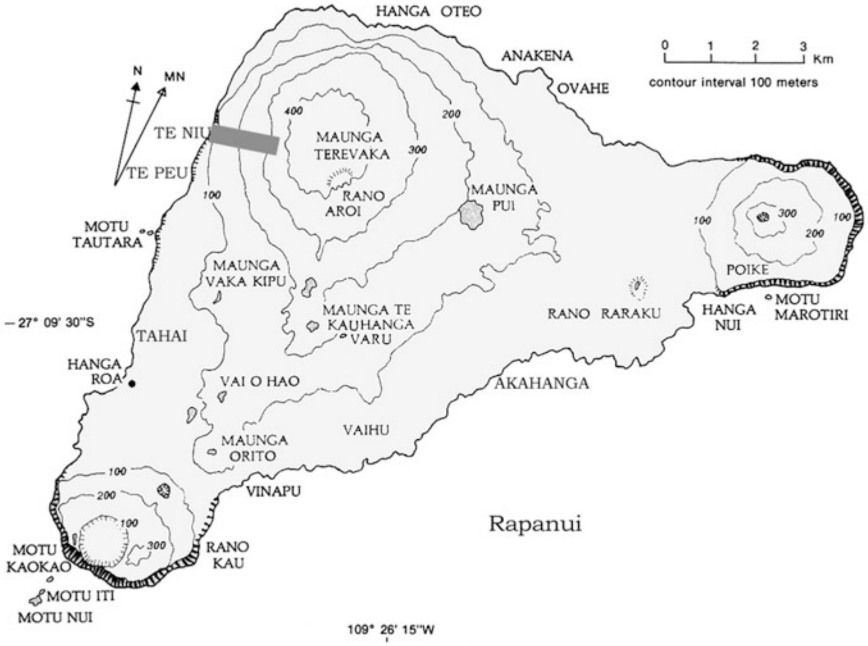

Fig. 18.1 Rapanui (Easter Island) with Te Niu Archaeological Survey Sector highlighted

described Rapa Nui in 1722 as an island predominately covered with grasses but having some wooded areas located inland from the coast. Cook (1821) and La Perouse (1797) documented the presence of plants related to agricultural production including some "coconut trees" in the interior of the island. Palmer (1868: 168) observed: "there were boles of large trees, *Edwardsia*, palm, and hibiscus, decaying in some places, when we visited the island . . . ". Thus, we may surmise that there were few palms remaining on the island and most of the Rapa Nui landscape was cultivated by 1700 CE.

What little information we have regarding the northwest coast, and specifically the land surrounding *Ahu* Te Niu had been recorded by La Perouse. For example, he also noted that rocks were used as a garden cover where cultivars were grown on the northwest coast. However, no one had previously surveyed or documented the settlement pattern, the gardens, or the history of ecological change on this part of the northwest coast at the time of the study in the late 1990s by the author.

A few early anthropologists visited this portion of the island. Routledge (1919) recorded that the part of the northwest coast north of *Ahu* Te Peu (Te Niu is the settlement located north of the Te Peu settlement) was associated with the descendants of Ava Rei Pua (Avarepua), sister of the founding lord, Hotu Matu'a. Her archeological description of Te Niu features was confined to describing a long, raised cobblestone pavement next to the Road of the Moai that crossed the upper region of Te Niu as:

> a pavement, generally by the roadside, neatly made of rounded boulders and edged with a curb; the form was said to be ancient. One of those on the west road was reported as specially dedicated to *matatoa*—which signifies victors or warriors—and the same was said of a differently made *ahu* on the south coast.
>
> (Routledge 1919:231)

Prior to the 1990s survey described in this chapter, the only archeological features defined at Te Niu related to a single image *ahu* at the Te Niu *ahu* complex at the top of a 100-meter-high cliff and the pavement on the Road of the Moai defined by Routledge as dedicated to the *matatoa*. There has been no mention of the settlement surrounding *Ahu* Te Niu prior to 1996. The image *ahu* had a rear wall of carefully carved and fitted basalt slabs and one large *moai*. Thomson (1891), the first person to assign names and numbers to most of the coastal *ahu,* assigned No. 12 to this *ahu* and was told by locals that it was named *Ahu* Ohau; he provided a sketch of its rear wall. Sixty years later Heyerdahl (1989:107) recorded this same *ahu,* using Thomson's sketch, as *Ahu* O*ahu*. Englert (1974) and Métraux (1940:297) in his ethnography referred to the *ahu* as Ohau. *Ahu* Ohau, however, is only one image *ahu* in an *ahu* complex composed of two and possibly three *ahu*.

This image *ahu* complex, now officially named *Ahu* Te Niu, was constructed during the 14th and 15th centuries at the cliff edge, approximately 900 m west of the platform described by Routledge. At least seven moai of varying sizes were at one time mounted upright on three platforms. These moai were brought from the Terevaka quarry on the south side of the island along a section of the Road of the Moai leading to the northwest coast. This road crossed over the Te Niu sector on a relatively level terrace about 900 m inland from the cliff and extended north to access other *ahu* along the northwest coast.

One research aim of this study at Te Niu was to find and describe the Polynesian gardens observed in the eighteenth century by Europeans visiting the island and describe their location in regards to the settlement believed to accompany the *ahu*. A second aim was to document the environmental changes and deforestation in the Te Niu landscape resulting from the establishment of those gardens.

The author's archeological survey (Wozniak 1998, 2003) documented and examined the *ahu* complex on the cliff edge and the settlement pattern of households and gardens between the image *ahu* complex and the cobblestone platform on the Road of the Moai mentioned by Routledge, and using a less rigorous procedure continued the survey inland up the slope of Terevaka for another 600 meters. A geomorphological study examining the stratigraphy inherent to the landforms of Te Niu was incorporated into the archeological research.

Cauwe and De Dapper (2015) carried out additional excavations at *Ahu* Te Niu during their study related to the Road of the Moai. Stevenson et al. (2015) have excavated in the Te Niu sector near the Road of the Moai in order to collect dateable material to establish dates for gardens at inland island sites. More recently the quadrangle 26, of which the Te Niu sector is a part, has been surveyed by Sonia Haoa and her colleagues (Haoa Cardinali and González 2007–2008) as part of the island-wide archeological survey.

Ecosystem surveys, consisting of soil (Alcayaga et al. 1975; Wright and Diaz Vial 1962) or extant plant surveys (Skottsberg 1953) were carried out in the early twentieth century. Early soil surveyors on Rapa Nui did not observe, or did not recognize the presence of the former palm remains, such as the root casts. It was the late twentieth century palynological and archeological work of Flenley and King (1984), Mann et al. (2003, 2008), Mieth and Bork (2015) and Rull et al. (2015) and others have demonstrated that the native ecosystem of Rapa Nui at one time was indeed a palm-dominated woodland. The multiple small circular casts (imprints) within pedogenic soil horizons were exposed during excavations or in profiles of exposed gullies (Flenley and King 1984; Mieth and Bork 2004; Stevenson et al. 2006) and recognized as evidence of palm roots. Palm pollen retrieved from marsh mud dates to >30,000 BP and resembles the pollen of Jubaea chilensis, native to Chile, in size and shape (Flenley and King 1984; Grau 2006).

The palynological studies of Flenley (1991) and others (Cummings 1998; Horrocks et al. 2013; Rull et al. 2015) and the anthracological examination of wood charcoal from *umu* ovens by Orliac (1998, 2000) and Pearthree (2003) have confirmed that a palm-dominated woodland ecosystem was present on Rapa Nui when Polynesians arrived on the island. Dransfield et al. (1984) named the extinct or extirpated palm *Phascalococcos disperta*. The palm resembles *Jubaea chilensis*, the Chilean Wine Palm, most closely (Dransfield et al. 1984; Grau 1998, 2006).

Rolett and Diamond (2004) suggest that the ecosystem on Rapa Nui was and is fragile and therefore subject to rapid deterioration by environmental changes and climatic aberrations. Using pollen cores from the marshes of Rano Aroi, Rano Kau, and Rano Raraku, Rull (2020) found that the palm forest thrived and diminished even before the arrival of the Polynesians. He suggests that these ebbs and flows of the forest were most likely due to climatic changes affecting palm growth and reproduction. Rull's pollen evidence (2020) also suggests that deforestation by colonizing Polynesians resulted in the formation of island-wide grasslands.

While palms formed the top canopy of the pre-human woodland, there was a middle canopy made up of small hardwood trees and shrubs and an understory of herbaceous plants and grasses according to Orliac (2000). She found that *Sophora* and *Sapindus* (which were present historically) were only two of the diverse native mesic hardwoods formerly present on the island prior to, and during the early human occupation. These included species of the genera of *Premna, Pittosporum, Syzgium, Myrsine, Elaeocarpus, Psydrax,* and *Coprosma*—genera found in mesic forests of other east Polynesian islands. Delhon and Orliac (2008:99) report that burnt endocarps and pieces of palm trunks found in excavations on Rapa Nui dated between the twelfth and fifteenth centuries. According to Orliac (2000:218), the palms, hardwood trees, and most of the native shrubs disappeared in the seventeenth century.

Evidence of a palm-dominated woodland forest in Holocene era soils has been exposed during excavations. These include casts of palm bulbs or bouls (base of trunks) in addition to palm roots (Bork et al. 2019; Dransfield et al. 1984; Flenley and King 1984; Mann et al. 2008; Mieth and Bork 2018; Stevenson et al. 2006; Wozniak 2003) since Palmer's visit in the nineteenth century. Casts of adventitious palm roots are commonly seen in the thick Oxisol and Inceptisol soils on Rapa Nui (Mann et al. 2008: 136). Palm microfossils, such as pollen and phytoliths, are present in the Te Niu soils (Horrocks and Wozniak 2008; Wozniak et al. 2008) and in the cores taken from the three marshy areas on the island (e.g., Flenley 1991; Rull 2020). These microfossils confirm the presence of past palm-dominated woodland biomes described by other researchers (Delhon and Orliac 2008; Orliac 2000) and also the subsequent cultivation of Polynesian cultivars (Whistler 1991) and the sweet potato from the Americas (Yen 1974). Rapa Nui soils and rainfall were especially conducive to the cultivation of sweet potatoes (Louwagie et al. 2006), which became a major crop on the island.

The topography on the northwest coast is one of wide level benches (treads) or concave swales (concave landforms) alternating with short steep slopes (risers) formed by the toes of Quaternary lava flows on Mt. Terevaka. Soil and sediment layers of varying thickness have developed in the downward sloping swales and on the level benches.

The topography of the Te Niu project area immediately inland from the cliff is comprised of four major tread and riser units. These four units extend inland for 1200 meters. The benches and swales concentrate water- and wind-entrained sediments in them. Outcrops of friable tuff and basalt bedrock occur at the higher elevations of the Te Niu project area (1000 to 1600 meters inland). Most of the soils at Te Niu below 300 MASL were grass covered at the time of the survey.

While early soil studies on the island (Alcayaga et al. 1975; Benedetti 1991; Mikhailov 1999; Wright and Diaz Vial 1962) described the soils as being thin, acid, and stony with moderate fertility, more recent studies show that the soils and sediments on Rapa Nui vary in thickness depending upon the landform on which they developed or were deposited (e.g. Mieth and Bork 2005; Wozniak 2003). These soil studies inform more about the effects occurring after the introduction of sheep and other hoofed animals to Rapa Nui in the latter half of the nineteenth century when sedimentation sharply increased. Sheep quickly killed the shrubs by stripping the bark off them; they also ate the grass to the roots (Thomson 1891). Lack of vegetation resulted in extensive erosion when heavy rainfall took place (Wright and Diaz Vial 1962).

The soil at Te Niu was classified as an Omotu soil grouping by Wright and Diaz Vial (1962) and as belonging to the Akahanga soil grouping by Benedetti (1991). Benedetti describes Akahanga soils as having a granular structure, a dark yellow-brown color, and having moderate to low water retention. Organic matter measured between 11 and 15% in his samples, but lacked various essential nutrients and tended to be quite acid, having a pH between 5.2 and 6.

While there are no permanent surface streams on Rapa Nui, heavy rainfall produces several intermittent streams on Terevaka, e.g., Quebrada Vaipú on the southern slope (Vogt and Kühlem 2018). Rainfall also penetrates into the ground and emerges at the land-sea interface from underground lava tubes (Routledge 1919:132). Less intense rains entrain sediments, forming sheetwash, which collects in the swales and on the benches. At Te Niu, sheetwash and rilling, described below, appeared to be the major hydrological phenomena affecting the transport of water and sediments rather than intermittent streams.

2 Research Questions

The research questions for the archeological and geomorphological study at Te Niu focused on:

1. Subsistence and resource use—What practices did the Rapa Nui people use for food production?
2. Environmental change—What long-term consequences resulted from the establishment of household structures and gardens and subsistence practices, resource use, and other cultural activities? Were variables other than subsistence involved in environmental alteration?
3. Archeological landscape formation and geomorphic changes—How do the spatial and temporal patterns of settlement features, activity areas, and environmental features observed in archeological and geomorphologic contexts provide evidence of land use activities over time?
4. Cultural landscape formation—How does the Te Niu evidence extracted from the geomorphological and archeological records explicate the interactions between humans and the island environment during the process of landscape formation?

To answer these research questions, the research at Te Niu included geomorphic, biogeographic, and paleoecological studies in order to reconstruct the environmental history of landscape formation. A pedestrian survey and a series of excavations were designed to identify garden areas and study areas of other cultural activities. Charcoal and obsidian artifacts were collected in order to date the context of natural phenomena and human activities. Extensive examination of soils and sediments and artifacts in the lab were carried out to confirm observations.

3 Methods: Archeological Survey and Geoarcheological Study at Te Niu

After identifying the Te Niu ceremonial structure and carrying out a pedestrian survey to establish the adjacent settlement pattern of household and ceremonial features, a series of systematic excavations were undertaken. Units 50 cm by 50 cm were excavated with trowels along transects in an east-west direction (the “prime transect”) extending one kilometer inland from the ramp of *Ahu* Te Niu on the coastal cliff. Two transects (each 500 meters long) were set perpendicular to the prime transect in a north-south direction. Thus, 20 excavations were carried out along the kilometer-long E-W transect beginning at *Ahu* Te Niu at the western end, and another ten along each of the two N-S transects (at 200 m E and 600 m E of the *ahu*) as shown in Fig. 18.2.

Each excavated unit was 50 m from the next along these transects. Three excavations were also completed at the front and three at the back of the *ahu*. Additional units were opened at several house sites and garden areas within 400 m of the *ahu*. At the excavations in targeted rock-covered locations, the physiographic context and soil stratigraphy at each of the units was documented; collected soils were submitted for chemical testing (phosphates) and for micromorphology studies described in Wozniak (2003). Radiocarbon and obsidian hydration dating were used

Fig. 18.2 Te Niu Survey Sector was a 500 m × 1600 m area divided into 50 m square units for the archeological survey and geomorphological study. Forty excavation units (50 cm × 50 cm) were placed every 50 meters along three transects, the prime East-West baseline, which extended from Ahu Te Niu to 1000 m up the western slopes of Maunga Terevaka, and two North-South transects perpendicular to the baseline transect at 200 m and 600 m from the ahu. Figure also illustrates the extent of household sites and gardens. Excavation unit location marked as small gray squares

to determine the timeframe of stratigraphic and structural changes that took place in pre-human soils as well as those changes occurring after the native ecosystem became a humanized ecosystem.

4 Results: Archeology and Geomorphology Survey at Te Niu

4.1 Soil Geomorphology at Te Niu

The series of excavations allowed views into the stratigraphy of various morphological landforms at Te Niu. The systematic excavation protocol exposed pedogenic soils of the former palm-dominated woodland. It also led to the recognition of humanly manipulated garden soil or anthrosols under discrete layers of small rocks (the lithic mulch). The stratigraphy observed in the excavation profiles also elucidated when traditional land use by the Rapa Nui people at Te Niu ended and when historic uses of the island for raising animals affected the landscape.

Soils and sediment layers at Te Niu were found to vary in thickness and stratigraphy according to the geomorphic context of the landform on which they lay. The bench and riser landforms at Te Niu are subject to erosional or depositional forces; however, some landforms were and still are alternately exposed to both erosion and deposition under different climatic conditions. Prior to the colonization of the island by Polynesians, pedogenic soils (often more than one meter thick) had formed under the ancient palm-dominated ecosystem, and the clay-rich soil still contains casts of palm roots centuries after those palms were removed.

Although the Te Niu area contains no marshes, the botanic, geological, and pedogenic evidence found here demonstrates that a palm woodland ecosystem had been present within the Te Niu project area, both prior to human arrival, and during the first centuries of Polynesian occupation.

Additional evidence of the long-term presence of a palm-dominated woodland includes the casts of palm trunks and fronds identifiable within the basalt lava flows at the cliff edge (Figs. 18.3 and 18.4). One of the solidified lava flows descending the western side of Maunga Terevaka contained casts of a group of four palm trunks; this flow was covered by several additional lava flows. The ages of the lava flow on either side of the red paleosol, 20–30 meters below the present land surface under *Ahu* Te Niu, have not been determined. At least four subsequent lava flows lay between the paleosol (observed in Fig. 18.4d) and the present soil surface at Te Niu, suggesting the paleosol was buried during the Pleistocene.

As Fig. 18.3 demonstrates, the cliff consists of numerous lava flows, many with paleosols sandwiched between them. Marcos Rauch of Conaf (Fig. 18.4b) indicates that he has found at least 28 such palm trunk casts along the northwest coast (personal communication 2021). Bork et al. (2019) found similar imprints at Anakena.

Fig. 18.3 Cliff face of Te Niu showing the alternate layers of lava flows and paleosols (former soil surfaces). Ahu Te Niu is at the top left corner of photo. Casts of three palm trunks are in photo center, 4th lava flows from the top. The white arrow designates location of the closely placed palm trunk casts

The basalt casts of four palm trunks along the Te Niu cliff shown in Fig. 18.4 range from 40 to 70 cm in diameter and are within 10 m of one another. The largest of the basalt palm trunk casts extends at an angle up from the paleosol (Fig. 18.4a, b, and d). Former leaf scars are visible in the casts (Fig. 18.4c). These scars bear a resemblance to the leaf scars present on *Jubaea chilensis* palms (Grau 2000, 2006).

Rat gnawed remains of palm endocarps were recovered from a cliffside cave at Te Niu (Fig. 18.5). These endocarps are similar in size and form to those of *Jubaea chilensis* (Grau 2006) and other endocarps found in protected areas on Rapa Nui.

Root casts of palms have been observed (Bahn and Flenley 1992; Mieth and Bork 2015; Mann et al. 2008; Mieth and Bork 2004; Van Tilburg 1994) within the former topsoils and clay-rich B horizons of pre-human soils at many different locations on the island, from sea level to 500 m at the peak of Maunga Terevaka (Bork et al. 2019). These casts represent the pores left when the cylindrical aerial rootlets, which extended from the base of the trunk (bole) into the soil, but remained as discrete pores in the clayey soil after the palm was cut down. The root structure of palms at Te Niu is similar to that found in living *Jubaea chilensis* palms on mainland Chile (Grau 2006).

Excavations at *Ahu* Te Niu exposed adventitious root imprints within pre-human soils. Charcoal composed of burnt palm endocarps, and pollen and phytoliths of palms and hardwoods found in stratigraphic contexts, all support a history of a palm-

Fig. 18.4 Palm trunk casts. a to d. From upper left, clockwise—(**a**) View of lava flow with openings of two casts of palm trunks. (**b**) Base of palm cast with Marcos Rauch of Conaf squatting on the paleosol. Marcos has found at least 28 additional palm casts along the west coast (personal communication). (**c**) Fossilized wall of 70 cm diameter palm cast showing the trunk scars. (**d**) Close-up of the red paleosol in which palms grew before being enclosed by hot lava

dominated ecosystem at Te Niu. Charcoal rings preserved in the soil under the *Ahu* Te Niu ramp were also exposed during excavation. The trunk structure of palms such as the *Jubaea chilensis* palm (and likely the extinct *Paschalococos dispersa* palm) consists of a 1–2 cm thick hard external cortex and a corky secondary cortex, about 5 cm thick. Fibrovascular and fibrous bundles of the water reserve system of the palm make up the central part of the palm trunk (Grau 2006). When burned the denser outer cortex would likely burn hotter and longer than the moist inner zone, thus leaving a circular imprint in the soil. This suggests that a palm was growing just prior to the conflagration that charred the vegetation where the ahu was to be built.

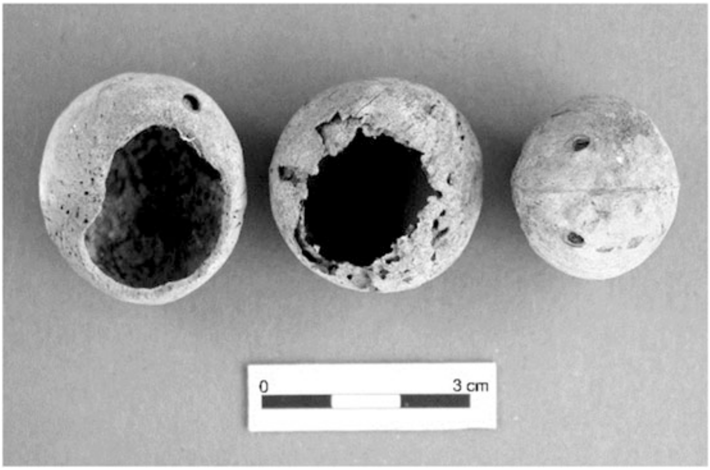

Fig. 18.5 Fossilized endocarps of the extinct palm of Rapa Nui found in a cliff cave below Ahu Te Niu. Marks of rat gnawing are visible on the two endocarps on the left. Scale = 3 cm

When people settled in the Te Niu area, they removed native trees to make room for ceremonial structures (*ahu*), houses, and house gardens. The palms were cut down, left to rot, or burned in place. A widespread burn event was exposed as a centimeter-thick charcoal lens under the *ahu* structure (See Fig. 18.6). This lens formed when people burned the native vegetation at the edge of the Te Niu cliff prior to the construction of the ceremonial *ahu* platform. The charcoal lens is visible in excavations in front and behind the two main platforms that make up the *ahu*; the lens contained palm endocarps, pieces of hardwoods, herbaceous material, and animal bones (rats and fish). How much time passed between the removal and burning of the woodland on the Te Niu cliff and the construction of the first platform at *Ahu* Te Niu was between years and decades after the burn.

Construction of the monument aided in retaining sediments from the upper slopes of the Te Niu sector. After the construction of the *ahu*, deposits of colluvium sediments were laid down in the Te Niu area; these sediments are especially visible in the excavation units at the *ahu* but are also seen in some of the systematic excavation units along the E-W transect in the down sloping swale east of the *ahu*. Stratigraphy exposed in the excavations demonstrates that certain landform surfaces continue to accrete colluvium, and wind-driven loess and that people have worked into the soil through various cultural activities. The soils exposed in excavations are composed of a complicated stratigraphy of pedogenic soil, deposited colluvium, and cultural material layers resulting from various activities. Some of these soil and sediment layers may have been altered, missing, eroded, or truncated over the 600 plus years of habitation here.

However, the results of various excavations at Te Niu indicated that a meter thick pedogenic soil, which developed under a palm-dominated woodland, is now covered with up to a meter-deep layer of sediments—both colluvium and cultural

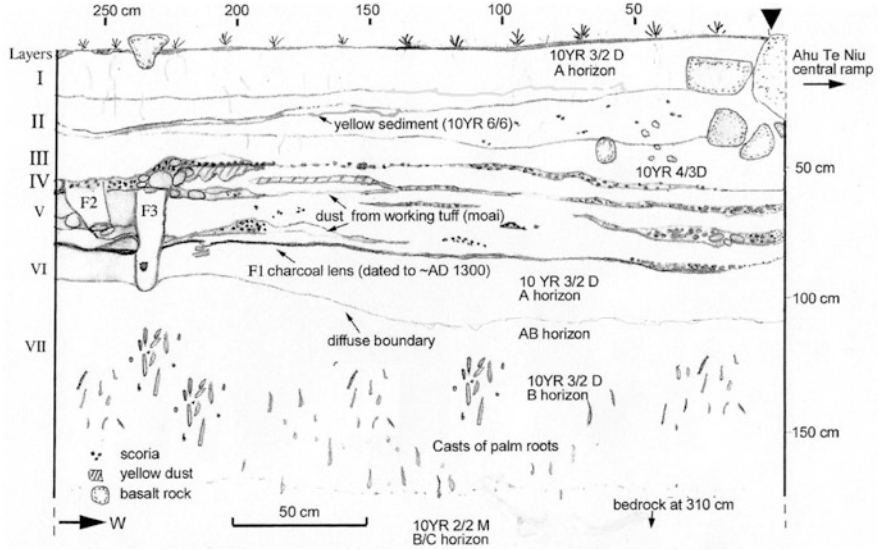

Fig. 18.6 South wall profile of Unit 26-1-1 at Ahu Te Niu extending from the alignment of boundary boulders outlining the ahu ramp (on the upper right). Repeated events of sediment deposition and cultural materials related to the reconstruction of the ahu structure after 1300 CE are evident. Layers I and II and Layer III represent historical sedimentation. F2 and F3 extending down from Layer IV may have been holes dug to place offerings (food plant material or a rat). Skeletons of multiple rats were uncovered during excavation; the rat bones were in little pockets of loose soil. An alternative interpretation is that the pits represent spaces made by shrubs that then died and decayed; later these were filled with sediments. Layer VI, under the charcoal lens dated to ~1300 CE represents the topsoil of the pre-human palm-dominated woodland. Layer VII represents the B horizon with casts of palm adventitious roots. Carbonized skins of palm roots collected at 150 cm depth in this unit had a ^{14}C date of 6329 to 6246 BCE (AZ12). The charcoal lens made up of palm endocarps at 90 cm depth gave dates of 1295 CE (AZ23), 1301–1378 CE (AZ25), and 1290 CE (Beta 78)

deposits laid down on the inland side of *Ahu* Te Niu after the initial *ahu* construction after 1300 CE. The colluvium deposits are the result of human-caused erosion and deposition after the forest uphill of *Ahu* Te Niu had been removed.

The survey and excavation protocol at Te Niu resulted in the surface rock concentrations being recognized as a lithic mulch covering gardening soils (Wozniak 1999, 2003). Discrete layers of rocks (the "lithic mulch" of rock mulched gardens discussed below) covered approximately 10% of the land surface in the research area (Wozniak 2003). These layers of rocks were similar to those described by Lightfoot (1996), who gave them the name "lithic mulch gardens." Similar discrete rock layers were found on top of garden soils elsewhere on Rapa Nui (Ladefoged et al. 2013; La Perouse 1797; Stevenson and Haoa 1998; Stevenson et al. 1999; Stevenson et al. 2002; Wozniak et al. 2008).

Along the protected southern edge of the large swale (protected by a remnant lava toe) just inland from the *ahu* excavations demonstrated that pedogenic soil similar to

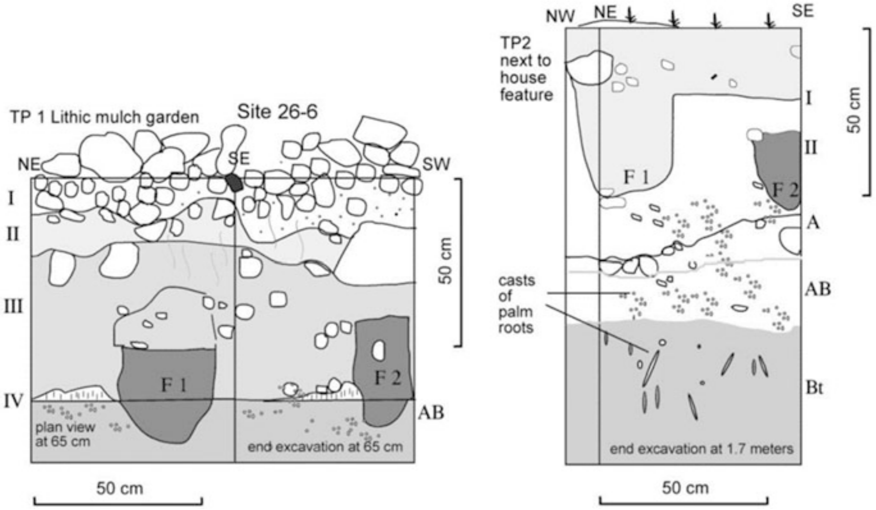

Fig. 18.7 Stratigraphic profiles of TP1 and TP2 at the Site 26-6 household. 26-6-TP1 is situated at the western boundary of the lithic mulched garden (26-7b). It is also next to, and inland of the house features. Note that the AB layer (the former topsoil) and Bt horizons contain palm root casts. Pit features F1 and F2 in both units are planting pits. Charcoal from F1 of TP1 at 65 cm depth dated to BP 435 +/− 40 (1444 CE)

that found in front of the *ahu* was prevalent. A residential complex site, designated as Site 26-6 and located 200 meters inland from the *ahu* had been built on this pre-human soil. The associated garden area, covered with a 30–40 cm thick layer of small rocks, was located on top of the pedogenic soil as well, as shown in Fig. 18.7 (Units 26-6-TP1 and 26-6-TP2). The excavation unit 26-6-TP1 was located on the western edge of a lithic mulched garden area labeled Site 26-7b, and was adjacent to, and inland of, the residential site 26-6. Unit 26-6-TP2 in Fig. 18.7 was located next to the house site (identified by its cobblestone pavement) and 4 m west from 26-6-TP1. Both of these units sat on top of the former palm-dominated woodland soil, which extended down to bedrock. Bedrock was exposed at 1.7 m depth in 26-6-TP2. A second excavation in the same 26-7b garden (named Unit 26F0) was excavated at the northern edge of the 26-7b garden. This unit intersected with the prime E-W transect of excavation units. The two garden units (26-6-TP1 and 26F0) were approximately 40 meters apart. Both Unit 26-6-TP1 and 26F0 showed evidence of soils that had been cultivated— a cultural layer of loose soil exhibiting planting pits (F1 and F2 in Unit 26-6-TP1, Fig. 18.7).

Soil profiles found within the swales and on the level treads at Te Niu display deeply buried horizons that formerly—i.e., prior to human occupation—were surface soil horizons developing under the palm-dominated woodland. The layers observed below the 55 cm depth in 26-6-TP 1 and 26-6-TP 2 (Fig. 18.7) include pedogenic soil layers with casts of palm roots. Construction of the residential house features about AD 1300 (680 CE) preserved the palm woodland soil structure. Thus, the pre-human soil profile at Site 26-6 lies 50 cm below the present land surface on bedrock uncovered at a depth of 1.7 m.

In general, the thick pedogenic soil layers found at Te Niu were at lower elevations (below 150 MASL and within 400 m inland of the *ahu*) in sedimentary contexts. At higher elevations, (over 150 MASL) thin soils and sediments generally less than 1 m prevail. The thinnest soils tend to occur in erosion-prone geomorphic contexts.

4.2 Formation of Anthropogenic Soil Horizons at Te Niu—Anthrosols

The swales and level areas at Te Niu served as garden areas. Soils in these geomorphic contexts display an anthropogenic layer—a matrix of loose, soft, charcoal-flecked, unaggregated soil 30 to 60 cm thick having distinct soil-filled planting pits. Cultivated soils on Rapa Nui often have charcoal, burned soil, and little marine shells as recounted by La Perouse (1797). He noted that Rapa Nui gardeners burned hardwood twigs and grasses to add to the soil, presumably for their nutrient value. Garden soil is technically a cultural deposit and forms an anthrosol – a soil formed or heavily modified due to long-term human activity. Anthrosols were found within the upper soil horizon in the rock-covered gardens, elsewhere in the household complexes, and at the *ahu*.

There is a distinct boundary between the garden soil horizon and horizon lying below it, which, at Te Niu, is usually a buried pedogenic topsoil, which developed in the palm woodland ecosystem. The buried topsoil horizon observed at Te Niu had subangular peds of high clay content and large pores made by the palm roots—pedogenic features typical of a palm-dominated forest. The boundary between the garden soil layer and the lower pedogenic horizon is marked with imprints typical of cultivation activities using hand tools (concave depressions or pits filled in with loose soil) in the more clay-rich horizons below. These pit features likely represent the last planting or harvest activity at that specific location. At times pits protrude from the anthropogenic soil layer into the lower horizons of the pedogenic soil.

Soil samples were collected and submitted for various tests, such as phosphate content and soil pH. Suspected garden soils were compared to soil horizons in other contexts to serve as controls. The pH tended to be neutral. The gardens in the proximity to the *hare moa* (chicken houses) tended to have a higher phosphate than other garden soils but most of the Te Niu soils displayed higher phosphate concentrations than control samples from other areas of Rapa Nui. Ladefoged et al. (2010) found similar variations in phosphate concentrations in their extensive island survey. However, anthrosols at *Ahu* Te Niu had the highest phosphate levels of all soils tested, possibly due to feasting or activities involving the dead that could increase phosphate content in soils.

In addition, the structure of soil horizons was analyzed to define the microscopic characteristics of each layer. This micromorphology study of thin sections (as per Davidson and Carter 1998; Macphail et al. 1990) confirmed macrostructural observations of former pedogenic development of B soil horizons (in this case a clay-rich Bt horizon) that formed under the palm-dominated woodland, or the presence of anthropogenic garden soils (Wozniak 2003).

The anthropogenic soil layer at Te Niu appears as organic, silty, and unaggregated and often has a higher content of fine gravels surrounded by organic matter or very small, sub-rounded, or subangular peds or charcoal particles at the center of these small peds. Clays and fine charcoal particles from this upper layer had washed down into the cracks and pores of the lower horizons (i.e., into the buried former topsoil or the pedogenic B horizon).

Garden soil layers at Te Niu are found in some grass-covered contexts, but more commonly they are found directly under a 20–40 cm layer of small rocks— rocks predominately 5 to 15 cm in diameter—making up a lithic mulch. "Lithic mulch" as defined by Lightfoot (1996) has also been referred to as "rock mulch." The lithic mulch may have helped limit erosion of garden soil during hard downpours but also the uneven surfaces of the lava rocks aided to hold the moisture as well as ameliorate temperature fluctuations in the soil during inclement weather. Layers of lithic mulch have been observed over much of Rapa Nui (Stevenson et al. 1999; Baer et al. 2008; Ladefoged et al. 2013), and in many locations around the world as part of a gardening strategy in areas having an abundance of rocks and soils exposed to extremes of temperature or precipitation (Lightfoot 1994, 1996). The Te Niu sector has rock-covered areas totaling a tenth of the total land surface in the Te Niu project area from the coastal cliff to 1000 meters inland. Isolated household gardens found at 1200 meters inland also have rock-covered areas. The upper potential garden areas were not tested for the presence of cultivated soils, however.

The excavation unit 26F0 (in the lithic mulched garden 26-7b discussed above) was situated along the E-W excavation transect and happened to coincide with an edge of a rock-covered garden in the center of a swale. The exposed profile indicates that a deeper garden soil layer that was formerly covered with rocks was subject to sedimentation events (likely colluvium deposited in a rainstorm). These sediments were then developed into another garden layer, which in turn was manually covered with another layer of small rocks. Thus, 26F0 has two garden soil layers, the upper anthrosol sandwiched between two layers of lithic mulch. The upper garden soil horizon was dated to the fifteenth century, which means the lower garden soil horizon likely represents one of the earlier gardens used at Te Niu.

While many of the garden soils at Te Niu were protected from environmental extremes by discrete layers of rock, not all gardens were protected by lithic mulch. Excavations in a walled *manavai* manifested a garden soil similar to that of lithic mulched gardens. Both garden contexts—lithic mulched garden and *manavai* gardens—are spatially associated with household complexes, and both are situated in geomorphic contexts that concentrate and hold rain runoff and have adequately deep soils for food production. Using such innovative garden structures, Rapa Nui gardeners were able to ameliorate environmental extremes related to moisture, winds, and temperature, and lack of shade.

4.3 Radiocarbon and Obisidian Hydration Dates Relating to Land Clearing and Human Activities at Te Niu

Pedogenic soil that had developed under a palm-dominated woodland was exposed during excavations at several sites in the Te Niu sector. Pre-human soil horizons were uncovered in front of the image *ahu*, at several household and garden sites, and during the systematic series of excavations. At *Ahu* Te Niu, a thick lens of charcoal composed of a centimeter-thick accumulation of palm and hardwood charcoal including burnt palm endocarps, lithic artifacts, and burnt food remains was revealed. This charcoal lens lay on top of a pedogenic soil horizon, the pre-human palm-dominated woodland soil horizons. Charcoal and palm endocarps from this lens were dated to 650–700 BP (approximately 1300 CE).

Below the charcoal lens, more than 135 cm below the present soil surface, samples of carbonized, conglutinated organic matter from palm root pores in the clay-rich B horizon were extracted for AMS dating (Table 18.1). Two samples gave dates of 7430 ^{14}C years (6683–5888 BCE at 2σ) and 9155 ^{14}C years (8736–7969 BCE at 2σ). These early Holocene dates seem to indicate that palms and the soils that developed under the palms had been present at Te Niu throughout the Holocene. Palm trunk impressions in the lava flows within the cliff at Te Niu extends the presence of palms to the Pleistocene.

Numerous radiocarbon dates at Te Niu demonstrate that activities related to construction and remodeling of the ceremonial *ahu,* gardening, and other activities occurred in the Te Niu settlement from AD 1300 through the mid-nineteenth century or later.

At the *ahu*, burnt remains of fish and Polynesian rat bones were found within hearths that had been set on top of the burnt remains of the charcoal lens discussed above. Radiocarbon dates from charcoal, e.g., AZ22 dated 325 BP (1481–1667 CE), retrieved from above the thick, widespread charcoal lens at the *ahu* give a time frame of early construction of *ahu* in the fourteenth and fifteenth centuries. AZ22 was composed of palm endocarps. Later remodeling of *Ahu* Te Niu occurred as late as the seventeenth century (e.g., Beta 79 was dated to 230 BP (1616–1952 CE). On top of the charcoal lens and associated hearths, several layers of colluvium sediments and cultural material—predominately made up of basalt rubble and crushed scoria from *ahu* monument construction- were also observed (Fig. 18.6).

Just above the charcoal lens in front of the *ahu* ramp (Unit 26-1-1) there was evidence of rilling, suggesting that prior to *ahu* construction rainwater and any water and entrained sediments were absorbed by the palm woodland thereby preventing erosion. In heavy storms what was not absorbed into the soil may have drained to the sea over the cliff edge. Once the vegetation was eliminated and the *ahu* structure constructed, overland rainwater flow with its colluvial sediments carried downhill in sheetwash were deposited on the upslope side of the *ahu* (as seen in Fig. 18.6) or washed down the cliff on the edge of *ahu*, possibly the causing the cliff collapse on the northern end of the *ahu* structure. (Soft unconsolidated sediments covering the cliff north of *Ahu* Ohau collapsed at some point prior to Thomson's 1886 visit (Thomson 1891).)

Table 18.1 Radiocarbon dates from Te Niu

Sample	Description	14C age	S.D.	1, 2 sigma	Lower cal	Upper cal	Relative area	Lower cal range BC/AD	Upper cal range BC/AD	Relative area
Code	**Gardens**	BP			CE/ BCE	CE/ BCE		CE/ BCE	CE/ BCE	
AZ27	26F@36cm LMG	545	40	1σ	1408	1440	1			
AZ27	26F@36cm LMG	545	40	2σ	1391	1456	0.991981			
AZ1	26-7b@65cm (=26-6-TP1)	435	40	1σ	1448	1502	0.799376	1594	1613	0.200624
AZ1	26-7b@65cm (=26-6-TP1)	435	40	2σ	1435	1517	0.660708	1539	1625	0.339292
AZ2	26-22b@51cm LMG	605	40	1σ	1388	1419	0.646483	1323	1345	0.353517
AZ2	26-22b@51cm LMG	605	40	2σ	1378	1438	0.604616	1308	1361	0.395384
AZ3	26-22C, Sq2@35 cm LMG	385	40	1σ	1546	1623	0.691478	1479	1513	0.308522
AZ3	26-22C, Sq2@35 cm LMG	385	40	2σ	1459	1631	1			
AZ4	26-36TP1@20cm manavai	210	60	1σ	1722	1810	0.530518	1651	1703	0.278428
AZ4	26-36TP1@20cm manavai	210	60	2σ	1643	1951	1			
AZ5	26-I0@25cm LMG	715	70	1σ	1278	1326	0.511237	1343	1389	0.488763
AZ5	26-I0@25cm LMG	715	70	2σ	1226	1406	1			
AZ6	26-T0@25cm LMG	415	70	1σ	1450	1512	0.505578	1568	1622	0.399911
AZ6	26-T0@25cm LMG	415	70	2σ	1428	1645	1			

(continued)

Table 18.1 (continued)

Sample	Description	14C age	S.D.	1, 2 sigma	Lower cal	Upper cal	Relative area	Lower cal range BC/AD	Upper cal range BC/AD	Relative area
	Household sites									
AZ9	26-6-TP5@25cm hearth	230	45	1σ	1729	1804	0.684683	1647	1687	0.315317
AZ9	26-6-TP5@25cm hearth	230	45	2σ	1634	1816	0.846625	1829	1892	0.097939
Beta320	26-6-TP7@65cm, F. 2	90	60	1σ	1878	1931	0.422843	1809	1840	0.242048
Beta320	26-6-TP7@65cm, F. 2	90	60	2σ	1797	1954	0.777531	1673	1740	0.222469
AZ7	26–6c,Sq2@45cm hare	680	45	1σ	1343	1389	0.636511	1299	1325	0.363489
AZ7	26–6c,Sq2@45cm hare	680	45	2σ	1286	1399	1			
AZ10	26-5-TP2@39cm hare umu	105	40	1σ	1878	1925	0.456362	1810	1838	0.265224
AZ10	26-5-TP2@39cm hare umu	105	40	2σ	1805	1954	0.831127			
Beta 80	26-50@30 cave hearth	550	110	1σ	1378	1493	0.724106	1306	1362	0.275894
Beta 80	26-50@30 cave hearth	550	110	2σ	1284	1627	1			
AZ26	26M250S @25cm hearth	240	40	1σ	1737	1799	0.699004	1649	1676	0.300996
AZ26	26M250S @25cm hearth	240	40	2σ	1720	1812	0.583059	1629	1710	0.343247
	LMG = lithic mulch garden									

	Ahu Te Niu	BP			CE/ BCE	CE/ BCE				
AZ23	26-1-1@89cm ramp	685	50	1σ	1344	1389	0.609182	1296	1325	0.390818
AZ23	26-1-1@89cm ramp	685	50	2σ	1281	1401	1			
AZ25	26-1-1@90cm ramp	650	40	1σ	1313	1358	0.726045	1380	1398	0.273955
AZ25	26-1-1@90cm ramp	650	40	2σ	1296	1407	1			
Beta 78	26-1-1@90cm_char lens	700	90	1σ	1282	1393	1			
Beta 78	26-1-1@90cm_char lens	700	90	2σ	1214	1436	1			
AZ14	26-1-2@60cm moai	230	60	1σ	1723	1809	0.5606	1641	1701	0.334078
AZ14	26-1-2@60cm moai	230	60	2σ	1625	1952	0.979692			
AZ22	26-1-2@180cm endocarp	325	40	1σ	1509	1579	0.705118	1620	1646	0.294882
AZ22	26-1-2@180cm endocarp	325	40	2σ	1481	1667	0.998922			
Beta 319	26-1-3@90cm under ahu	570	50	1σ	1392	1442	1			
Beta 319	26-1-3@90cm under ahu	570	50	2σ	1381	1455	0.812382			
AZ24	26-1-3W@85cm ahu rear	535	40	1σ	1411	1443	1			
AZ24	26-1-3W@85cm ahu rear	535	40	2σ	1393	1458	1			
AZ28	26-1-4@100cm endocarp	555	40	1σ	1404	1437	1			
AZ28	26-1-4@100cm endocarp	555	40	2σ	1390	1453	0.963869			
Beta 79	26-1-4@100cm_ahu rear	230	90	1σ	1719	1812	0.425755	1638	1710	0.301079
Beta 79	26-1-4@100cm_ahu rear	230	90	2σ	1616	1952	0.885694			
AZ13	26-1-4@130cm ahu rear	535	50	1σ	1407	1448	1			
AZ13	26-1-4@130cm ahu rear	535	50	2σ	1387	1483	0.953301			
AZ8	26-1-6@20cm crem	375	45	1σ	1537	1626	0.77064	1492	1519	0.22936
AZ8	26-1-6@20cm crem	375	45	2σ	1460	1637	1			

(continued)

Table 18.1 (continued)

Sample	Description	14C age	S.D.	1, 2 sigma	Lower cal	Upper cal	Relative area	Lower cal range BC/AD	Upper cal range BC/AD	Relative area
AZ20	26-1-6@20cm crem bone	380	45	1σ	1541	1624	0.719837	1482	1515	0.280163
AZ20	26-1-6@20cm crem bone	380	45	2σ	1458	1635	1			
	Ahu Te Niu plaza									
AZ12	26-1-1 palm pores 150 cm	7430	200	1σ	6453 BCE	6082 BCE	1			
AZ12	26-1-1 palm pores 150 cm	7430	200	2σ	6683 BCE	5888 BCE	1			
AZ11	26-1-5 palm pores 135 cm	9155	138	1σ	8405 BCE	8293 BCE	1			
AZ11	26-1-5 palm pores 135 cm	9155	138	2σ	8736 BCE	7969 BCE	1			
CALIB	C14 dates calculated in 2006 as per: Stuiver, M, Reimer, PJ (1993) and McCormac et al. (2004)									

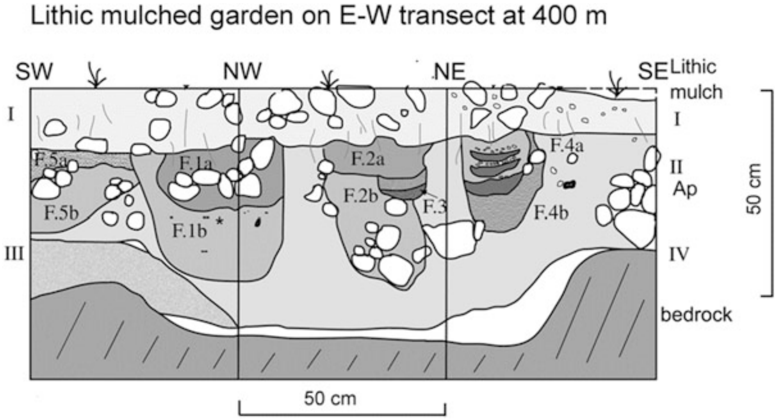

Fig. 18.8 The 50 cm × 50 cm unit 400 m east of the ahu was placed within a lithic mulched garden. Excavation exposed several planting pits, which appear to have been reused more than once. Distinctive soil color and texture varied with depth. Feature 1b, for example, was an older planting pit and F. 1a was a more recent use of that same pit. Charcoal (*) from planting pit F. 1b, within Layer II, the Ap layer, was AMS dated to 1285 CE (calibrated)

Three thick layers of colluvium deposits in front of the *ahu* ramp lay on top of the charcoal lens and rock rubble covering the pre-human soil horizons; each measured between 20 and 35 cm thick. The first colluvium laid down was 35 cm thick and was deposited in several episodes. The colluvium was interspersed with three to four lenses of red scoria gravels and rock dust; these lenses were likely associated with *moai* or paenga carving activities at the *ahu* and the dispersal of scoria gravel used as a covering on the *ahu* surface. The rock shelter (26–50) sediments containing the palm pollen and phytoliths (Cummings 1998) were radiocarbon dated (sample Beta 80) to the fourteenth century (550 BCE) and obsidian hydration dated to between 1398 and 1778 CE (Table 18.2).

Charcoal samples were retrieved from within the anthropogenic soil horizons of lithic mulched gardens and household sites. Sample AZ5, taken from along the prime transect at a unit 400 m inland (Fig. 18.8), and AZ 7, from under a house site (26–6-Sq2) 200 m inland from the *ahu* were also dated to 1300 CE. The two samples retrieved from the remnant topsoil of the former palm woodland strongly suggest that land was cleared by fire for house sites and garden space at about the same time the cliff edge was cleared for the ceremonial *ahu*.

Charcoal (AZ27) retrieved from another transect unit, at the edge of the garden 26F0 at Te Niu (Fig. 18.5), and AZ1 from Unit 26-6-TP1 (Fig. 18.4), (both units from within the 26-7b garden), and AZ6 in the garden at T0, 950 m inland provided fifteenth-century dates. The presence of burned material in the garden soils helps to date the gardens but also confirms La Perouse's observation in 1786 that Rapa Nui gardeners added burned matter to the garden as a horticultural practice.

The fire pit from Unit 26-M250S (likely associated with a residential site south of the Te Niu project area) dated 240 +/−40 BP (1720–1812 CE). In the household

Table 18.2 Obsidian hydration dates from Te Niu

	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Date	+/−	Range (CE)	S.D.
Residential sites																						
26–5-2, ‘hare umu’	1810	29	1592	45	1804	29	1666	40	1626	43	1605	45	1765	33	1626	43					**1592–1810**	38.4
26–6c Sq 1 &Sq 2	1407	56	1675	40	1857	24	1852	25	1861	24	1861	24									**1407–1861**	32.2
26-M0 ‘residence’	1750	35																			**1750**	35
26–50 ‘rockshelter’	1716	44	1756	40	1756	40	1668	48	1778	38	1630	51	1405	66	1430	64	1442	63	1398	66	**1398–1778**	52
Garden sites																						
26-F0_26-7b rock mulch	1634	43	1806	30	1806	40	1811	29	1794	31	1800	30	1800	30							**1634–1811**	31.9
26-22B ‘rock mulch’	1740	35	1806	30	1806	30	1806	30	1806	30											**1740–1806**	31.3
26-L0, ‘rock mulch’	1794	31	1750	35																	**1750–1794**	33
26–36-1 ‘manavai’	1833	27	1776	32																	**1708–1746**	29.5
26–36-2 ‘manavai’	1800	30	1788	31																	**1685–1714**	30.5
Ahu Te Niu																						
26–1-1 ramp	1642	43	1667	41	1806	30	1782	32	1659	42	1744	35	1833	27	1740	35					**1642–1833**	35.6
26–1-1 W ramp	1822	28	1659	42	1667	41	1770	33													**1659–1828**	36
26–1-2 ahu 1	1667	41	1828	27	1674	40															**1667–1828**	36
26–1-3 rear wall ahu 2	1667	41	1642	43	1659	42	1582	47	1667	41	1642	43									**1582–1667**	42.8
26–1-3 W rear ahu 2	1690	39	1712	38	1697	39	1705	38													**1690–1712**	38.5
26–1-4 rear wall ahu 1	1651	42	1634	43	1667	41	1617	44	1667	41											**1634–1667**	42.2
Ahu plaza_26-B0	1788	31																			**1788**	31
Ahu plaza_26-C0	1764	34																			**1764**	34

Obsidian Hydration dates determined by CMStevenson 1997/ revised 1998/recalculated 2021

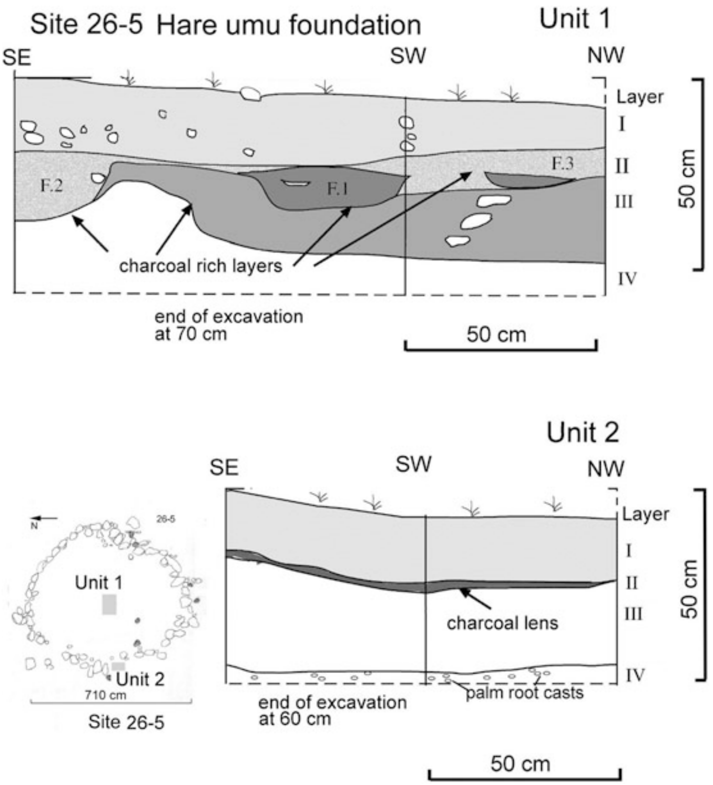

Fig. 18.9 Site 26-5, Units 1 and 2. Profiles of excavations within the *hare umu* (26-5) associated with residential site 26-6. Unit 1 at the center of a circle of large rocks had several charcoal lenses typical of fire pits. Layer II and III of Unit 1 were made up of ash and charcoal-rich sediments. Unit 2, Layer 2 was a 1 cm thick charcoal lens composed of burnt grasses that likely represents the collapsed burned roof of the *hare umu*. Obsidian pieces found in F.2 of Unit 1, a thick ash lens, dated to between 1400 and 1726 CE. Layer I in both Unit 1 and Unit 2 represents a sedimentation layer deposited after the last uses of this site for cooking and the burning of the grass roof. Layer IV of Unit 1 and Layer III of Unit 2 appeared to be a mixture of sediments and topsoil from the palm forest. The casts of palm roots were uncovered at the top of layer IV in Unit 2

Site 26-6, AZ9, from Unit 26-6-TP5, situated on a mound with multiple fire pits and an *umu pae*, produced a date of 230 BP+/−45 (1659 to 1816 CE). Charcoal (AZ10) sampled from an *umu* in the middle of a former *hare umu* structure at 26-5 (Fig. 18.9), next to the residential site 26-6, dated to 105 BP+/− 40 and a pit at 26-6-TP7 (Beta320) near another buried *umu* oven dated 90 BP, indicating continued settlement use of the Te Niu landscape during the eighteenth and nineteenth centuries.

Environmental or climatic perturbations (volcanic eruptions or storms) may have served to increase or diminish the thickness of the pre-human soils on some landforms at Te Niu through rare erosion and sedimentation events. Any deposited sediments of such events would have been incorporated into the topsoil of the woodland. However, the preeminent evidence of sedimentation observed at Te Niu relates to the prehistoric land clearance by colonizing Polynesians and historic pastoralism after Euro-Americans took control of the island. These latter events appear in the upper portion of stratigraphic profiles exposed in many units excavated at Te Niu, including on those landforms retaining the pedogenic soil of the palm-dominated woodland.

The thickness of the pre-human pedogenic soils found in front of *Ahu* Te Niu matched the thickness of the sediments deposited on top of the palm woodland soils over the 800 years since colonization by Polynesians. The presence of several sedimentation events preserved at the *ahu* indicates that erosion was occurring periodically at higher elevations on Terevaka, resulting in the movement of colluvium sediments downhill. A second round of *ahu* construction took place, as evidenced by the presence of another layer of rock rubble and a lens of rock dust, in the early fifteenth century. This construction was for a second platform (the platform known as *Ahu* Ohau). Additional sedimentation events occurred during the same timeframe, resulting in the deposition of a 20-cm thick colluvium layer. A period of environmental stability followed and pedogenic features began to develop in these sediments under a grass cover. A third construction project event—possibly an early eighteenth century remodel of *Ahu* Te Niu, combining the three platforms into a single *ahu*, occurred after a period of environmental stability.

Similar pedogenic soil horizons were found at some of the household complexes and gardens at Te Niu discussed above. Pre-human palm-dominated woodland soil horizons at house site 26-6 attained a thickness of almost 1.5 meters, as shown in Fig. 18.4 (Unit 26-6-TP1). The garden associated with this house site had a 40 cm to 50 cm anthrosol, a thick garden soil layer resulting from cultivation of the top layer of the pre-human pedogenic soil, which was likely enhanced by deposition of sediments (colluvium and loess) as well as the addition of burned material (charcoal and ashes) added by the Rapa Nui gardeners.

Unit 26-F0, within the same garden area as Unit 26-6-TP1, contained two 50 cm thick anthropogenic soil horizons separated by a rock layer. The 26-F0 unit was located at a low point along a downward sloping swale. The lower layer of soil—40 cm to 50 cm thick—was covered by rocks, which in turn were covered with more sediments. These were then cultivated prior to 1500 CE and covered with more small rocks.

The topography of the northern part of the M series of excavations (M50N to M250N), 600 meters east of the *ahu* at 200 MASL, represents the western extent of a broad tread within the Te Niu project area. Although one might expect a sedimentary surface on this bench. The result was that deposition or erosion occurred depending upon the energy of the overland flow with its entrained sediments. The soil profile of M200N demonstrates that thin layers of sediments have been deposited. There is no evidence of pedogenic horizons.

At the southern end of N-S transect, the unit at M250S (Fig. 18.10), demonstrated both pedogenic soil development with the presence of palm root casts in a relatively thin horizon. Sedimentation was preserved at this location on top of the pre-human soil. At about 1655 CE (240 BP radiocarbon years), a hearth was set up

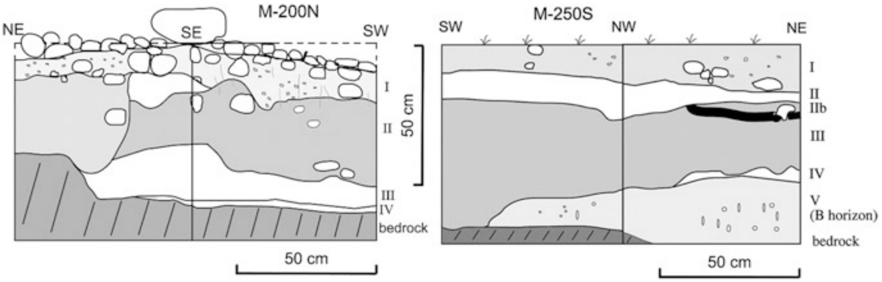

Fig. 18.10 Profiles of the test units 600 m inland from the Te Niu cliff. The M-200 N unit is a thin soil used as a lithic mulched garden. Layer I are sediments collecting on the lithic mulch covering Layer II, which is a buried palm woodland topsoil turned into a garden soil (Ap). Layer III appears to be a transition between the topsoil and Layer IV, a saprophytic bedrock. The M-250S unit demonstrates two layers of colluvial sediments on top of a disturbed former woodland topsoil (Layer III) on which a hearth was built. Charcoal from a hearth within the buried A horizon dated to 1656 CE. A thin AB transition layer lies over the B horizon with casts of palm roots in Layer V

at this location on top of the former woodland topsoil. Twenty-five centimeters of colluvium sediments covered the fire pit by the late twentieth century. Whether the 25 cm of sediments were deposited in multiple thin layers or laid down as one large deposition episode could not be determined. If the deposition occurred before or after the introduction of quadrupeds to the island could not be determined. However, within the past 200 to 300 years, increased sedimentation is apparent within the swales and on the level treads of the stepped surfaces at Te Niu.

4.4 Summary of Results: Conversion of the Former Palm-dominated Woodland Ecosystem to Gardens

The presence of a Pleistocene palm-dominated woodland on Rapa Nui is preserved in lava flows making up the Te Niu cliff. The preserved casts include palm trunks with their leaf scars and fronds in lava; the paleosol in which the palms grew identified at the base of one of these palm casts below *Ahu* Te Niu. Casts of conglutinated palm roots in the pedogenic soils that developed under a palm-dominated forest are found in front of *Ahu* Te Niu. When radiocarbon-dated, it appears that palms were growing in the extant surface soils at Te Niu since at least 8000 BCE, as the lava developed into a deep, clay-rich B horizon typical of a palm woodland.

Burned endocarps found in the charcoal lens preserved under the *ahu*, in a charcoal-containing hearth in a cave nearby, and in soils from several gardens, all provided radiocarbon dates indicating that the islanders settled at Te Niu by at least 1300 CE. The extensive presence of charcoal dated to 1300 CE suggests that land was cleared using fire prior to settlement and that native vegetation closest to the

Te Niu coastal cliff was the first to disappear. However, over the following century, evidence presented indicates additional land was cleared for residential sites and gardens as far as 1000 meters inland from the cliff.

Soil samples collected for pollen and phytolith studies confirm that a former forest of palms and other endemic tree, shrub, and herbaceous species grew at Te Niu, and that the same soils in which the native plants grew were later turned into garden soil used to grow Polynesian cultivars and sweet potatoes in the fourteenth century when people settled on the northwest coast of Rapa Nui.

Pedogenic soil horizons developed under palms, shrubs, and herbaceous plants that colonized the soils at Te Niu throughout the Holocene. The depth of the soil horizon infiltrated with palm root casts suggests that weathering and humic additions worked to form topsoil in which palms and other plants could get a footing and start the process of pedogenesis during the Pleistocene.

Palms apparently continued to grow during the fifteenth to seventeenth century at Te Niu as evidenced by the dating of burned palm endocarps found in both the *ahu* plaza and retrieved from garden soils. Although the volcanic ash soil of Rapa Nui supported a palm-dominated woodland during the Pleistocene and at least remnants of a palm forest lasted through at least 300 years of human occupation at Te Niu (1300 to 1600 CE), the palm clearing activities led to a cycle of erosion and sedimentation events at Te Niu as the Polynesian colonizers established their home and gardens and constructed their ceremonial landscape of *ahu* and moai. Given the absence of trees that might create shade for and stabilize the garden soil, techniques needed to create a sustainable cultivation regime were developed. Structures like the walled garden or lithic mulch were brought into use.

5 Discussion and Conclusions of the Te Niu Landscape Study

The native, or pre-human, ecosystem at Te Niu (and on Rapa Nui as a whole) can be described as palm-dominated woodland. The extant soil stratigraphy exposed at *Ahu* Te Niu attests to at least 10,000 years of pedogenesis of volcanic soils under a palm woodland biome. The formation of the palm woodland topsoil was due to weathering of bedrock and the addition of humic matter from the vegetation the soil supported.

The native landscape palms at Te Niu became a cultural landscape with a revised ecosystem of Polynesian cultivars. The charcoal retrieved during excavations at *Ahu* Te Niu, and also at the household Site 26-6, gave radiocarbon dates that established early land clearing at Te Niu began about AD 1300, within a couple of centuries of Polynesian colonization on Rapa Nui. Vegetation was burned at the *ahu* location. Food remains of Polynesian rats and fish and palm nut endocarps were left amid the burnt vegetation, thus confirming that humans caused the burning at Te Niu.

The *Ahu* Te Niu complex, constructed over the two centuries after AD 1300 acted as a sediment trap, collecting eroded deposits in front of the monument. In addition to providing a history of soil erosion and sedimentation events after Polynesian settlement, the *ahu* structure itself had preserved the geomorphic history of the forest soils prior to Polynesian settlement. There is no indication that pedogenic soils under the *ahu* were eroded prior to human occupation at Te Niu. Outlines of palm boles and other tree trunks and roots are present within the palm-dominated woodland soil horizons.

However, the present surface soil layer (i.e., the extant topsoil) in the Te Niu project area is now made up of predominately historically deposited sediments (colluvium). On the upper slopes of Terevaka, gullying and rilling are common erosion features; these are seen over much of the northwest coast, including Te Niu. Colluvium sediments infuse the grass roots of the grasslands now present at Te Niu, and the soil is developing typical grassland ped characteristics.

Soil stratigraphy at Te Niu indicates that erosion and sedimentation due to natural or human-caused events since colonization were sporadic and potentially catastrophic. Thick colluvium layers were observed at lower elevations at Te Niu. These were dated to shortly after AD 1300, again in the late seventeenth century (e.g., at M250S), and more recently, during the period of sheep ranching (e.g., profiles of units at Site 26-5 in Fig. 18.9 and at the *ahu* in Fig. 18.6).

Although erosion and sedimentation occurred as a result of land clearing by Polynesians, the overall effect is that on certain landforms much of the native stratigraphy, which formed under the palm-dominated woodland, remains in place. There is no discernable evidence of erosion in the stratigraphy prior to the arrival of humans. Once humans arrived on the island, widespread sedimentation erosion events occurred and can be identified in swales, within the *ahu* plaza, at the edge of the cliff, and under some low elevation garden soils as colluvium sediment layers.

Homes and gardens at Te Niu were established in swales and on level treads extending the settlement and gardens from the coast to 1 km inland from *Ahu* Te Niu by 1400 CE. The use of the woodland soil for gardens resulted in the disappearance of the palms and other vegetation that had produced the fertile palm woodland soils. The forest soil was planted with Polynesian cultigens and the American sweet potato.

The Rapa Nui gardeners, aware of the susceptibility of their garden soil being eroded away, developed new improved methods to protect their gardens since the land was steep and thus prone to erosion during heavy rains. However, rainfall provided the only moisture for food production. One strategy used by the Polynesian colonizers was the use of lithic mulch, a surface rock layer protecting the garden soils from erosion and allowing more rain to penetrate into the root systems of cultigens (Wozniak 2003; Louwagie et al. 2006; Mieth and Bork 2018). Another technique was the use of walled enclosures (*manavai*). The horticultural practices of lithic mulch or *manavai* walls were added at some point during the prehistoric occupation, most likely after the loss of trees near gardens exposed the soil to desiccation and erosion.

Beginning 150 years ago under the influence of Euro-Americans, much of Rapa Nui, including Te Niu became pastureland. Overgrazing and use of fire to induce new grass growth have resulted in increased soil erosion on sloped landforms and increased sedimentation on level landforms. Sedimentation events that occurred during the late eighteenth and first half of the nineteenth century (as in Fig. 18.6) are preserved at the *ahu*, for example. Here historic sedimentation resulting from sheep grazing can be seen to equal that of the 500 to 550 years prior. At household sites, (for example, Site 26-6 and the associated *hare umu*. Site 26-5, situated along the edge of the central swale) the amount of historic sedimentation (post-nineteenth century) also equaled the thickness of the sediments deposited during the entire prehistoric period of Polynesian occupation.

In great part, the extant Te Niu topsoil is made up of sediments loosened by activities of the sheep, cattle, and horses introduced to the island in the late nineteenth century (Métraux 1940; Mieth and Bork 2005). Although sheep were removed in the 1960s, free-running cattle and horses remain. William Mulloy was able to document with photos in the early 1960s (negatives are stored in the archives of the Rapa Nui Library, Museo Fonck in Viña del Mar, Chile) that a heavy sedimentation layer covered the grass-covered plaza inland of *Ahu* Te Niu just prior to the expulsion of the sheep. A period of environmental stability, during which time organic matter has been incorporated into the former sediments and granular ped structures formed. However, Te Niu grasslands, like much of Rapa Nui was, and is, subjected to repeated field burning events that expose the topsoil to additional erosion by wind and rain.

While much of the recent Rapa Nui literature refers to the idea of a collapse of society resulting from environmental changes, such as the detrimental effects of deforestation (e.g., Bahn and Flenley 1992; Diamond 2005), it does not appear that those living at Te Niu suffered a prehistoric collapse due to ecocide. Carbon-14 dates (Table 18.1) and obsidian hydration dates (Table 18.2) from various household, garden, and *ahu* contexts indicate that gardening, household, and ceremonial activities were ongoing until the nineteenth century at Te Niu. These findings are in accord with Mulrooney (2013) or Mieth and Bork (2018), who concur that the people of Rapa Nui continued to carry on their daily activities in settlements along the coast throughout prehistory. It was the Europeans and Americans, and their microbes, invading Rapa Nui that decimated the Rapa Nui people and confined the few remaining families to the town of Hanga Roa.

The damage incurred by the intense erosion in the aftermath of the historic introduction of sheep, cattle, and horses and associated pasture management practices that has damaged the landscape at Te Niu and Rapa Nui as a whole is matched in the twenty-first century by the large influx of tourists on a small island requiring additional infrastructure, food and water, and tourist diversions the island is not sustainably able to provide.

Acknowledgments The author is grateful to the Consejo de Monumentos, Rapa Nui, and the Consejo de Monumentos Nacionales de Chile for permission to work on Rapa Nui. I also thank our island collaborators, Jose Miguel Ramirez and Marcos Rauch of CONAF, and Sonia Haoa Cardinali, Maria Atan Pakarati, Tirae Pakarati, Osvaldo Pakarati, and Enrique Pizarro for their assistance and support. I would also like to thank Chris M. Stevenson for assisting with obsidian hydration dating, University of Arizona AMS lab for their services and advice, Professors William S., Ayres, Pat McDowell, Aletta Biersack, Roger Green, and Pat Kirch for their input while in the field and for fruitful discussions afterward. I also thank the reviewers of this paper for suggesting how to better my argument. The field and lab work was funded by the Fulbright Foundation, the National Science Foundation, and the Sasakawa Young Leaders Fellowship Fund (Sylff), and the University of Oregon graduate school.

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Part V
Collapse or Resilience?

Chapter 19
Environmental Change and Cultural Continuity: Extraordinary Achievements of the Rapanui Society after Deforestation

Andreas Mieth, Annette Kühlem, Burkhard Vogt, and Hans-Rudolf Bork

1 Introduction

The exact timing of the first settlement of Rapa Nui is still subject of debate. Some authors argue for a settlement around 800 to 1000 AD (Steadman et al. 1994; Martinsson-Wallin and Crockford 2002; Mieth and Bork 2010). Other authors advocate the scenario of initial settlement around 1150 AD at the earliest (e.g., Hunt and Lipo 2006; DiNapoli et al. 2020). Undoubtably, however, the first settlers found an island covered in pristine woodland. The presence of an initially dense vegetation consisting of relatively few tree species and an understory of diverse shrub species, herbs, and ferns has been extensively documented in recent decades by palynological, anthracological, and geoarcheological research, and most recently summarized in detail by Rull (2020b). A now extinct palm species of the Cocosoidae subfamily played a dominant role in the species composition of the woodland. The palm species was probably closely related to the Chilean wine palm (*Jubaea chilensis*), whose exact taxonomic classification either to the genus *Jubaea* or as a separate species of a new genus *Paschalococcus* has been discussed (Dransfield et al. 1984; Zizka 1991). Biotic evidence for the former existence of more than one palm species has also been discussed (Delhon and Orliac 2007). The former existence of the now extinct palm species is undoubtedly proven by their remains

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_19

in geoarchives and/or anthropogenic contexts: pollen, phytoliths, charred wood, and especially by nutshells (endocarps) that appear either as deposits in protected places or as charred pieces in fireplaces. The most impressive indication of the former spatial distribution of the palm-dominated woodland is provided by palm root imprints preserved in the autochthonous soils that are attributable to the respective locations of individual trees. These imprints were found by Bork et al. (2019a) on more than 80% of Rapa Nui's surface area and up to an altitude of 500 m asl on the Terevaka volcano. In their latest calculations, the authors arrived at a total number of 19.7 million palms that once grew on Rapa Nui.

In the first centuries after the arrival of the Polynesian settlers on Rapa Nui, the human impact on the island's forest ecosystem remained relatively minor. There may have been local clearings for the construction of settlements and cultural sites, which changed the natural woodland into an anthropogenically altered forest ecosystem. However, horticulture with introduced crops as an essential form of land use took place for several centuries under the protection of the forest canopy. The islanders created loose, humus-rich garden soils (anthrosols) through mechanical soil cultivation, presumably in combination with organic mulching. Calculations show that millions of planting pits which form these anthrosols were carefully inserted between the individual locations of the palms. These anthrosols represent the oldest verifiable traces of cultivation on Rapa Nui, and they contain practically no charcoal (Mieth and Bork 2010). Anthrosols from this first phase of gardening have recently been found also on the southern slope of the Terevaka volcano at 375 m asl at the edge of the Quebrada Vaipú, not far from the study area described in this chapter (Bork et al. 2019b).

In the first half, at the latest in the middle, of the thirteenth century, the Rapanui then began to successively clear extensive areas of Rapa Nui's woodland. It is undisputed that this clearing process was accompanied by burning. Along with the clearing, the occurrence of charcoal in the cultural layers increased significantly. Over the course of approximately four centuries, the deforestation finally extended over the entire island, divided into spatial-temporal phases (Rull 2020a, b; Cañellas-Boltà et al. 2013; Mieth and Bork 2010). According to the simplified hypothesis that was put forward in the pioneering phase of paleoecological research, the forest was first eliminated in the coastal areas and only in the later phase in the higher elevations of the island (cf. Flenley and Bahn 2003, p.165). This was not confirmed in studies that are more recent. Instead, early evidence of forest clearance was found even on the remote Poike Peninsula at above 100 m asl (Mieth and Bork 2003). Seco et al. (2019) found evidence for intense forest clearance around 1070 AD at Rano Kau above 100 m asl., and the investigations described in this chapter show for the southern slope of the Terevaka volcano at ca. 240 to 275 m asl that the forest was cleared before ca. 1220 to 1290 AD. These findings not only contradict the thesis of a so-called late settlement around 1200 AD put forward by some scholars (e.g., Hunt and Lipo 2006) but also show that the clearing of the forest and the associated land use, settlement, and cultural processes were spatially and diachronically complex and did not follow a simple pattern (cf. Rull 2020a, p 225ff).

The loss of the forest had severe consequences for the ecosystem and the culture. Plant and animal species dependent on the forest were decimated or became extinct (cf. Steadman 1995). Thus, biotic and material resources were lost. The meso- and microclimate changed significantly, with far-reaching consequences for the cultivation of crops. After the loss of the forest cover the soils were unprotected and exposed to desiccation, wind, and heavy rain. Soil erosion first washed away fertile anthrosols on steeper slopes. Then, the unfertile, weathered volcanic rock underneath these garden soils was eroded, partially washed or blown into the sea, or deposited in downslope areas. In turn, not only gardens but also cultural sites in the depositional areas were shrouded or buried by sediments (Sherwood et al. 2019; Mieth and Bork 2003, 2017; Vogt and Kühlem 2018; Stevenson et al. 2006; Mann et al. 2003).

The extensive diminution of natural resources, the massive complications for horticulture, and the destruction of cultural installations in combination with the extremely isolated location and limited area of Rapa Nui suggest that the logical conclusion would be a cultural and social collapse as a consequence of the complete deforestation. Accordingly, the pioneers of archeological research on Easter Island such as Mulloy (1979) but also more recent paleoecological studies, e.g., by Flenley and Bahn (2003) postulated a causal connection between the deforestation of the island and a presumed massive decline, or even collapse, of the Rapanui society in the pre-contact period. Diamond (2005) repeated this thesis in his best-selling book "Collapse" with reference to the undoubtedly far-reaching consequences of the deforestation.

However, in recent years there has been an increase in research results that clearly contradict the collapse theory (e.g., DiNapoli et al. 2020; Simpson and Dussubieux 2018; Mieth and Bork 2015; Flas 2015; Boersema 2015; Stevenson et al. 2015; Mulrooney et al. 2010; Hunt and Lipo 2007). The authors of such studies by no means negate the extreme challenges that the dramatic forest loss on Easter Island posed for the Rapanui. But, recent investigations show that the Rapanui society was able to successfully contend with the consequences of the man-made changes to their environment and to secure the continuity of their culture with targeted and effective adaptations until the arrival of the first Europeans.

To counteract the impending loss of fertile soil, the Rapanui developed the technique of lithic mulching (Wozniak 1999). They covered the garden soils on the deforested areas with stones obtained from local quarries. On the surface of the soils, the stones protected them from wind and water erosion, from drying out, and from severe temperature fluctuation. Stones placed in the planting pits provided nutrients. Organic mulching also maintained and improved soil fertility

(Ladefoged et al. 2010). Over the course of about four centuries, the inhabitants of Rapa Nui spread approximately 1.14 billion stones on the garden soils. The amount of labor required to accomplish this probably far exceeded that of creating the *moai* and erecting the numerous *ahu* (Bork et al. 2004; Mieth and Bork 2005). Besides stone mulching, other new horticultural techniques were developed. They were diverse in their design and adapted to specific growing conditions of the different crops. Amongst these features are *manavai*, *pu*, planting circles, stacked boulder concentrations, and others (cf. Stevenson et al. 2002; Wozniak and Stevenson 2008).

The adaptation to new horticultural techniques is only one of various examples of how the Rapanui withstood changing environmental conditions. Despite the fact that natural factors such as the extreme geographical isolation, the subtropical climate, the low biodiversity (especially regarding the diminution of (still) available tree species), and the scarcity of fresh water, posed particular challenges for survival on the island. The research results presented in this chapter provide further evidence of such a successful convergence of environmental and cultural change on Rapa Nui.

2 Freshwater Resources and Freshwater Access on Rapa Nui: The Quebrada Vaipú

Compared to many volcanic islands in Polynesia where rivers and springs are abundant, easily accessible fresh water is a scarce resource on Rapa Nui. Even the earliest European explorers, desperate to reprovision their drinking water after long crossings, remarked on the scarcity and brackish quality of the water (cf. la Pérouse 1994: 65; Hixon et al. 2019). The fact that such a vital resource was not readily available posed a real challenge to the successful colonization of the island.

The sources of surface water on Rapa Nui are few. In pre-contact times the three crater lakes, Rano Aroi, Rano Raraku, and Rano Kau, stored most of the available surface water (Rull 2020c). The access to the water and its quality was less than ideal. In the case of Rano Kau accessing the water meant a perilous climb down the steep cliffs of the crater walls. Rano Aroi is located on the highest part of the island with no evidence of bigger settlements in the vicinity. The formation of peat in the lake (cf. Horrocks et al. 2015; Margalef et al. 2014) indicates that the water is paludal, acidic, and rich in tannins. The water of Rano Raraku is of rather poor quality as well, due to its high iron and aluminum content (Hanif 2018: 48). Extended dry climatic phases may have additionally reduced the water resources in the crater lakes (Rull 2020b: 222ff). Clan boundaries and the related taboos may have also limited the access to the crater lakes.

Freshwater was more abundant in some of the subterranean caves that riddle the island. But again, the access was probably restricted by taboos and in many cases physically challenging (cf. Ryn et al. 2010). In most areas the aquifer of the island was too deep to be reached by hand-built wells (cf. Herrera and Custodio 2008). But in the littoral areas where the aquifer is much closer to the surface there are a number of wells and water basins (cf. Hixon et al. 2019; Englert 2012; Forster 1777).

According to oral traditions, Hotu Matu'a, the legendary king of the first settlers of Rapa Nui, was aware of the problem of freshwater accessibility. He ordered wells to be built and, on his deathbed, ascertained that there was a supply of drinking water even in times of drought (Englert 2012: 286).

Droughts seem to have been a recurring calamity on Rapa Nui (Mann et al. 2008, Englert 2012, Rull et al. 2015, Rull 2020b: 222ff, Rull 2020c). Just a few months without substantial rainfall were enough to deplete the water reserves. Englert describes how priests would perform rituals in the mountains to bring rain that was so essential for the crops and for drinking water (Englert 2012: 290–291). Rainfall monitoring by Stevenson et al. (2015) shows that today the mean annual rainfall can locally be up to 2000 mm a year depending on height asl and exposition to the prevailing trade winds.

The role of coastal seeps for the fresh water supply was recently investigated by DiNapoli et al. (2019) and Brosnan et al. (2018). They conclude that despite its brackish nature coastal seeps played an important role in supplying drinking water. However, diatom analysis on dental calculus could demonstrate that individuals from different areas on the island relied on different drinking water sources (Dudgeon and Tromp 2014). Skeletons found on the south and southeast coasts have a high frequency of diatoms that are indicative for standing ponded water. Skeletons from the northeast and north coast show diatoms that typically develop in ephemeral water that originates in one of the many shallow basins (*taheta*) that are hacked into outcrops across the island. Survey data by Morrison (2012) show a significant number of such *taheta* on the northwest coast and also at high elevations. These investigations show that even those small receptacles were important in supplying the Rapanui with drinking water.

Englert points out the difficulty of transporting water, mentioning only gourds as possible vessels, albeit with only small capacity (Englert 2012: 282). Another means of transport described by him are spongy roots that absorbed water and were then wrapped in banana leaves for transport (Englert 2012: 282). Again, only a small amount of water could be carried this way.

Nowadays the Quebrada Vaipú is the only seasonal stream on Rapa Nui that carries a significant amount of water every year. It runs down the southern flank of the Terevaka volcano from the Rano Aroi crater lake to the shore at O Pipiri (Fig. 19.1). Its upper course lies within a mostly collapsed lava tube; in a limited area the roof of this tube is still intact and the water runs underground. Today the stream only carries running water after strong or prolonged rainfall. That this unique water course once held a great importance to the Rapanui is attested to by many hydraulic installations along the course of the creek.

Fig. 19.1 Aerial view of the Quebrada Vaipú on the southern flank of the Terevaka volcano (drone image: Christian Hartl-Reiter, DAI)

The stream is fed by Rano Aroi lake. In prehistoric times the outflow of water was controlled by modification of the lake outlet. At the lake outlet the Rapa Nui excavated the saprolite to a depth of 1.5 m in order to increase the amount of water flowing out if required (Fig. 19.2). This made it possible to let water run down the Quebrada Vaipú independent of rainfall. A side effect of the increased outflow was the reduction of the lake surface height and thus a significant reduction in evaporation rates. During the phase of intense sheep farming in the twentieth century the pre-contact facility was filled with sediment and a dam was raised. The new dam significantly increased the lake level height and thus the evaporation of lake water.

All along the course of the stream there are a number of prehistoric hydraulic installations such as bank enforcements, anthropogenic cascades, canals, basins, and retaining walls. The mouth of the Quebrada Vaipú lies in a small bay called O Pipiri, close to the ceremonial center of Akahanga (Fig. 19.3). Here again, the water is directed into a basin that is part of an elaborate series of megalithic constructions before flowing into the sea.

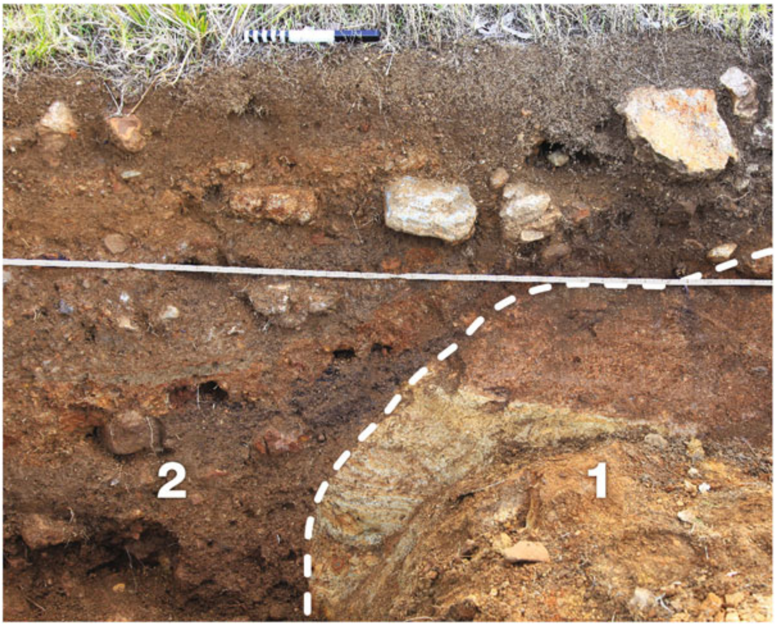

Fig. 19.2 Outlet at the southern edge of Rano Aroi lake. In prehistoric times, the Rapanui cut an artificial outlet into the saprolite. In the European period of sheep farming in the twentieth century, the outlet was filled with heterogeneous sediment and a dam was raised. (1) in situ saprolite, (2) prehistoric outlet filled with sediment (photo: Hans-Rudolf Bork)

The main practical reason for the installations along the course of the stream surely was to slow and control the flow of the water and to minimize the effects of erosion and flash floods (Vogt and Kühlem 2017: 327). Other important reasons seem have been to control the access to the water and to the enforce access taboos, resulting in the transformation of the landscape along the course of the creek with a strong ritual component (Vogt and Kühlem 2018; Kühlem 2016).

It is noteworthy that settlement structures in the vicinity of the Quebrada Vaipú are not more frequent than the general site distribution on the island as demonstrated by a large-scale survey in the late 1970s and early 1980s (cf. Cristino et al. 1981). DiNapoli et al. 2019 showed a strong correlation between the location of nearshore water sources and the location of *ahu* and settlements. Since inland access to freshwater is an even rarer commodity, one would also expect a concentration of settlement structures along the course of the only significant seasonal stream. The fact that this is not the case points towards a limited, regulated, and/or sanctioned access to the water in the Quebrada Vaipú. The most elaborate architectural framework for this water management was found at the site of Ava Ranga Uka A Toroke Hau in the very center of the island (Fig. 19.3).

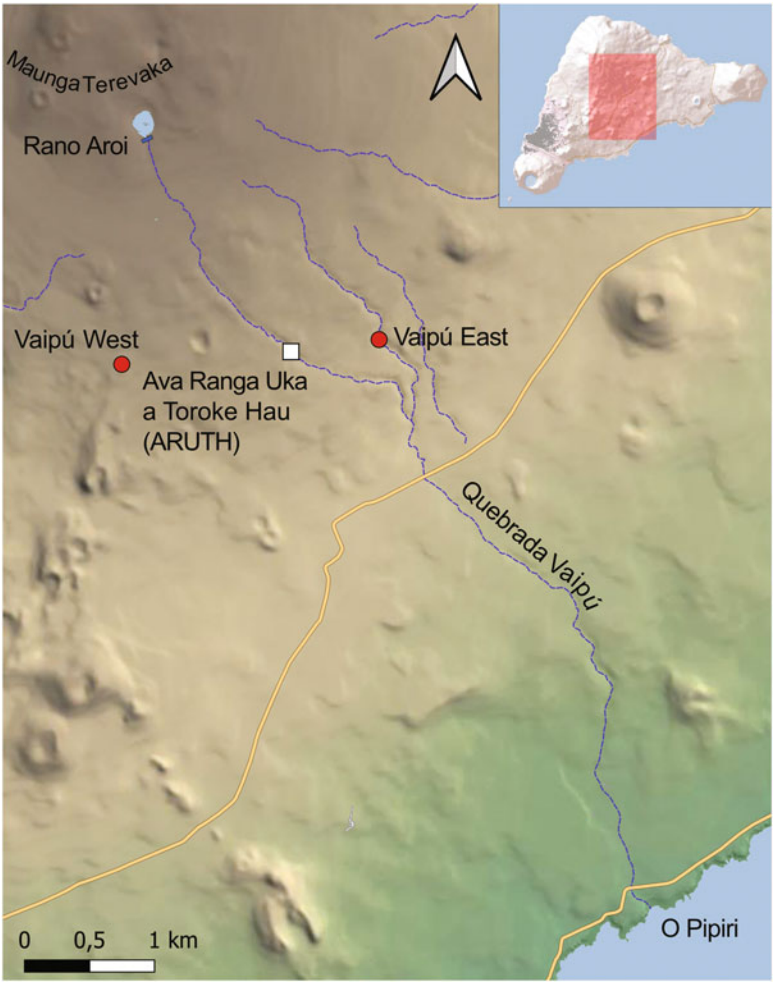

Fig. 19.3 Study sites on the southeastern flank of the Terevaka volcano (graphic: Christian Hartl-Reiter, DAI)

3 Monumental Installations at Ava Ranga Uka A Toroke Hau in the Quebrada Vaipú

The site of Ava Ranga Uka A Toroke Hau (hereafter ARUTH) is unique in many respects. It comprises an elaborate system of hydraulically active architecture alongside ritual elements that have completely transformed a segment of the valley in the center of the island (Fig. 19.4). The site lies in a widening of the Quebrada Vaipú. Besides the immense landscape alteration caused by large areas of stone mulching on Rapa Nui (see above), the degree of landscape transformation at Ava Ranga Uka A Toroke Hau is without parallel on the island.

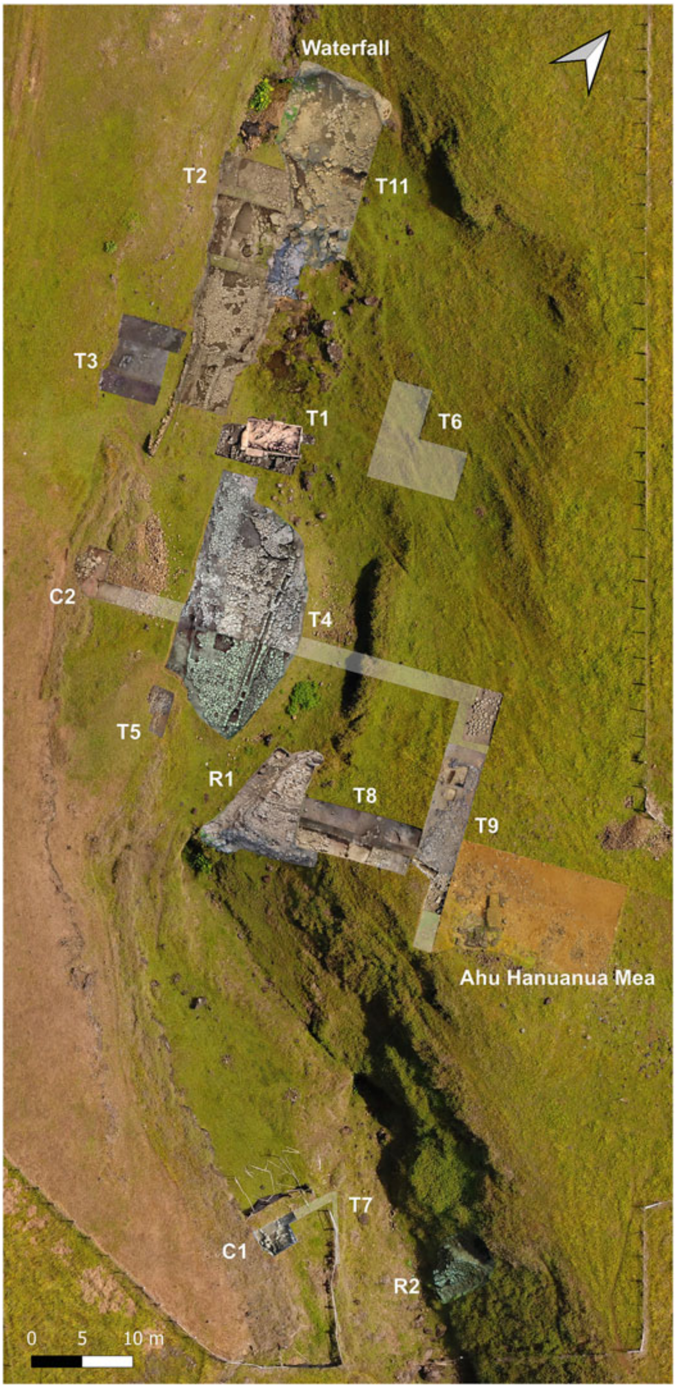

Fig. 19.4 Composite photo of the ARUTH site showing the widening of the Quebrada Vaipú and with the location of the waterfall, the Ahu Hanuanua Mea, Cave 1 (C1), and the different excavated trenches. The numerous paved areas are shown as georeferenced orthophotos (photo/graphic: Christian Hartl-Reiter, DAI)

Apart from the unique hydraulic features ARUTH is also the location of the most inland *ahu* on Rapa Nui. Ahu Hanuanua Mea, or "Rainbow Ahu," has a single *moai* that rests on its front with its base on the *ahu* masonry. It is a rather small *moai* of 3.34 m in height (Kozub and Kozub 2019) and it does not have carved eye sockets, which is characteristic for most of the statues standing on *ahu*. The fact that an image *ahu* is associated with the site of ARUTH attests to its religious significance and the fact that it was under the control of religious and/or political elites (see below).

The transformation in the widening of the valley begins at a small waterfall at the northern end of the site. Often there is only a small rivulet coming down the cascade but after even a few hours of intense rain the water comes gushing into the kolk. The edge of this natural pool was fortified by a massive stone wall (T11). A few remains of paving stones indicate that the entire floor of the basin was once paved. South of the kolk lies a big rockface with a perfectly circular *taheta*, a small shallow basin, carved into the rock.

In the streambed there are two canals that guide the water out of the kolk. One runs alongside a curved terrace wall that fortifies the western bank of the quebrada, the other runs underneath a series of big stone blocks and then follows the natural course of the streambed. Over time the area around the kolk was disturbed by the force of water but the remains of pavements and stone walls show that it was once intensely transformed.

A massive terrace of almost two meters in height runs along the western bank of the creek (T2, T3). It consists of a stone packing and is bordered by a retaining wall. In the lower levels of the northern part of the terrace a water basin, canals, and an elaborate circular oven made from rounded beach pebbles (*poro*) were found. The surface of this terrace is covered in an extensive pavement which later was concealed by an anthropogenic layer of highly compacted soil with a high content of charcoal. This sequence of pavement and compacted soil, as well as a circular pit in the paved area is analogous to the findings in the central area of the site (T4, see below).

A little further down the course of the creek lies a monumental rectangular stone basin made from *paenga* blocks, which are usually found as the foundation stones of boat-shape houses (*hare paenga*) (Vogt and Moser 2010; Vogt et al. 2018). The humid conditions in the basin enabled an extraordinary preservation of different seeds that were deliberately placed in a cache underneath a layer of white clay. A multitude of gourd seeds (*Lagenaria vulgaris*) possibly indicates the former use of gourds as vessels for water. In addition, 227 fragments of palm endocarps were found. Two endocarps were radiocarbon dated. The first showed an age of 1500–1620 cal AD (these and all further radiocarbon results refer to 2 sigma modeled dates), and the second was dated to 1460–1580 cal AD, giving a time for the construction of the basin (cf. Fig. 19.17; Table 19.1: No. 3, 4). These dates also show that palm trees still grew somewhere on the island by the second half of the fifteenth century and possibly even into the seventeenth century. Two other dates from directly above a small paved area inside the stone basin returned dates of 1530–1640 cal AD, and 1550–1670 cal AD (Table 19.1: No. 2, 1).

Table 19.1 List of 14C-dates from cultural contexts in Ava Ranga Uka A Toroke Hau. 14C-dates were calibrated with SHCal20 (Hogg et al. 2020). Bayesian phase modeling of the ages was performed using OxCal 4.4 (Bronk Ramsey 2009). No. 1–4 previously published in Vogt and Kühlem (2018). No. 18–21 previously published in Out et al. (2020) and here re-calibrated with SHCal20

	AMS-Lab-ID	Sector	Depth bls (m)	Height asl (m)	Age (yr BP)	+/−	δ13C (‰)	Age (yr cal AD, 2δ) (SHCal20)	Modeled calibrated age (yr cal AD, 2δ) (SHCal20)	Sample material	Anthracology	Context
1	Erl-13250	T1	1.35	267.06	349	40	−24.9	1464–1471 (1.6%) 1481–1651 (93.9%)	1550–1670	Charcoal	tbd	Megalithic basin, directly above pavement
2	Erl-13247	T1	1.45–1.63	266.78 to 266.96	384	40	−27.4	1458–1632 (94.5%)	1530–1640	Charcoal	tbd	Megalithic basin, directly above pavement
3	Erl-13248	T1	1.62	266.79	360	39	−23.4	1463–1472 (2.4%) 1480–1648 (93%)	1500–1620	Charcoal	palm endocarp	Megalithic basin, under pavement
4	Erl-13249	T1	1.68	266.73	307	39	−22.8	1500–1601 (48.5%) 1611–1674 (39.2%) 1740–1756 (2%) 1763–1799 (5.8%)	1460–1580	Charcoal	palm endocarp	Megalithic basin, under pavement
5	COL3982.1.1	T4	0.55	268.66	366	36	−24.9	1463–1473 (3%) 1479–1642 (92.4%)	1550–1660	Charcoal	tbd	Fireplace, layer 11

(continued)

Table 19.1 (continued)

	AMS-Lab-ID	Sector	Depth bls (m)	Height asl (m)	Age (yr BP)	+/−	δ13C (‰)	Age (yr cal AD, 2δ) (SHCal20)	Modeled calibrated age (yr cal AD, 2δ) (SHCal20)	Sample material	Anthracology	Context
6	COL4569.1.1	T4	0.67	268.17	443	33	−26.4	1436–1510 (72.7%) 1550–1560 (1.2%) 1579–1623 (21.6%)	1490–1630	Charcoal	tbd	Planting pit, layer 12
7	COL4568.1.1	T4	0.79	267.90	338	33	−19.7	1496–1657 (95.4%)	1480–1600	Charcoal	palm endocarp	Layer 10
8	COL4564.1.1	T4	0.99	268.47	495	32	−20.8	1408–1489 (94.5%)	1450–1510	Charcoal	palm endocarp	Fireplace, layer 5
9	COL4565.1.1	T4	1.02	268.38	506	33	−23.5	1404–1464 (94%) 1472–1480 (1.5%)	1450–1500	Charcoal	palm endocarp	Fireplace, layer 5
10	COL4567.1.1	T4	1.14	267.57	412	32	−25.9	1450–1518 (52.2%) 1537–1628 (43.3%)	1450–1500	Charcoal	tbd	Posthole, layer 2
11	COL3979.1.1	T4	1.31	267.90	475	35	−27.7	1417–1504 (87.9%) 1595–1616 (7.5%)	1440–1490	Charcoal	tbd	Palm tree planting pit, pavement 3
12	COL3980.1.1	T4	1.35	267.88	426	35	−24.2	1445–1514 (59.7%) 1544–1625 (35.8%)	1440–1480	Charcoal	sophora sp.	Fireplace, pavement 3

(continued)

13	COL3981.1.1	T4	1.47	267.88	438	35	−27.4	1437–1513 (66.4) 1556–1625 (29%)	1420–1470	Charcoal	tbd	Fireplace, pavement 3
14	COL4566.1.1	T4	1.52	267.41	557	32	−28.4	1329–1334 (1.1%) 1393–1450 (94.4%)	1390–1450	Charcoal	tbd	Pit, layer 2
15	KIA 46459	T7	1.06	260.10	650	25		1303–1363 (71.1%) 1380–1403 (24.4%)	1300–1410	Charcoal	tbd	Anthropogenic debris layer, layer 5
16	KIA 46460 (1)	T7	1.68	259.48	725	20		1281–1319 (51%) 1355–1385 (44.4%)	1270–1380	Charcoal	tbd	Anthropogenic debris layer, layer 4
17	KIA 46460 (2)	T7	1.68	259.48	770	30		1226–1311 (83.7%) 1360–1382 (11.8%)		Charcoal	tbd	Anthropogenic debris layer, layer 4
18	Beta-321021	Vaipú East	0.16		320	30	−25.10	1502–1595 (60%) 1615–1665 (35.4%)	1500–1670	Charcoal	tbd	Fill pit 2b
19	KIA 49033	Vaipú East	0.19		443	28	12,39	1440–1508 (76.7%) 1588–1620 (18.8%)	1430–1620	Charcoal	tbd	Fill pit 2b
20	Beta-321020	Vaipú East	1.46		680	30	−27.1	1292–1394 (95.4%)	1290–1400	Charcoal	tbd	Fill pit 1
21	KIA 48426	Vaipú East	1.46		807	17	−23.61	1226–1282 (95.4%)	1220–1290	Charcoal	tbd	Fill pit 1

On a lower level a canal seems to connect this basin to the central area of the site (T4). A small, paved area also seems to be a continuation of the extensive pavement that once spanned the entire width of the valley. The area between the stone basin T1 and the central area T4 was strongly affected by destruction due to a flash flood (see below). Therefore, a definite connection could not be established.

The central area of the site (T4) is characterized by a sequence of pavements and anthropogenic layers that created a platform with a cultural stratigraphy of up to 6 m in height (Fig. 19.5; details see below). The large-scale excavations of the upper pavement (Pavement 3) showed that it spans the entire area and is intersected by two canals. The eastern canal is connected to a shallow stone trough at the northern end of the platform and terminates in a small trapezoid basin at its southern end (Fig. 19.6). The canals are shallow and narrow with a rather small flow volume. This must be seen in the light of the scarceness of fresh water on the island, bearing in mind that during most of the year the deliberate opening or closing of the outlet at the Rano Aroi crater lake determined how much water came down the Quebrada Vaipú.

Three radiocarbon results date the extensive pavement with the water canals in the central part of the site: 1440–1490 cal AD, 1440–1480 cal AD, and 1420–1470 cal AD (cf. Fig. 19.17; Table 19.1: No. 11–13).

In a continuation of the western flank of the *ahu*, a massive retaining wall (R1) reaches across the creek bed. It is constructed by a succession of fine soil and stone packings and has a stone facing (cf. Vogt 2013). The construction was too loose to serve as a dam that holds back water. Instead, it seems to have served to slow the flow of water through the site. Forty meters further downstream a second massive wall, that is very similar yet of smaller dimensions, was built into the streambed (R2). Most probably both constructions were destroyed by the same flash flood that eroded the western sides of both walls.

On the western escarpment between R1 and R2 a small cave (C1) was excavated (cf. Moser 2013). The use in pre-contact times is attested to by lithic tools and manuports in the excavated layers. The area directly in front of the cave was intensely used as attested by stone structures and fireplaces. Within the valley of ARUTH this seems to be the only area where settlement activities took place, albeit on a small scale. The findings in the archeological layers and post-contact sheep bones on the surface inside the cave demonstrate a long use of this part of the site. Just below the cave lies profile T7 that runs along the western bank of the Quebrada and was analyzed in detail (see below).

4 The Stratigraphy of the Monumental Installations in the Central Area of ARUTH (T4)

In the central area of the site (Fig. 19.4, T4) it was possible to identify different phases of site use. The stratigraphy consists of up to 6 m of cultural deposits with different use-surfaces (Fig. 19.5). The body of layers forms an artificial platform on

Fig. 19.5 Embankment profile showing the succession of pavements and compacted layers of trench T4 (photo: Burkhard Vogt)

Fig. 19.6 Orthophoto of T4 with partially covered canal and stone-rimmed palm tree planting pits (photo/graphic: Christian Hartl-Reiter, DAI)

the western bank of the Quebrada. The eastern edge of this platform was eroded by the stream during an extreme runoff event (see below). The resulting embankment profile shows a succession of three pavements that are separated by compacted layers (cf. Kühlem 2016, Kühlem et al. 2014; Fig. 19.5).

The above-mentioned Pavement 3 that spans the entire widening of the valley is the lowest level of large-scale surface excavation that was reached to date (Fig. 19.6). It corresponds to the uppermost pavement in the embankment profile. Even though the direct connection between this pavement and the paved areas around the megalithic basin T1 is disturbed, the stratigraphic context and the height of the pavement slabs indicate that Pavement 3 of T4 merges with the pavement around the basin.

There are several noteworthy features within the excavated paved area of T4. A number of circular stone-rimmed pits were found amidst the pavement slabs (Fig. 19.7). In ten of them, in situ palm root imprints were visible, demonstrating that a small grove of the now-extinct palm species grew in the central area of ARUTH and the trees were integrated into the paved area. In some of the pits the root clusters were over 1 m in diameter. The assumed closest genetic relative of the extinct Rapa Nui palm, the *Jubaea chilensis*, grows mainly in diameter for the first 20 years, before growing tall (Guzmán et al. 2017). Also, the roots at the base of the trunk tend to be wider than the trunk itself. If this was also the case for the palm trees in the central area of ARUTH, then they need not have been large and mature specimens. The radiocarbon dates for the succession of layers in T4 show that the palm trees most probably did not have time to grow to their full height between the time when they were planted to when the area was altered again (see below).

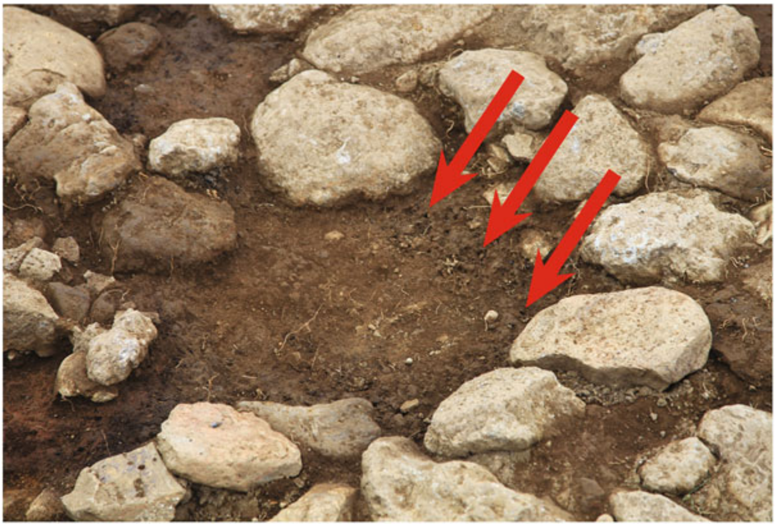

Fig. 19.7 Stone-rimmed palm tree planting pit with root imprints (marked by arrows) (photo: Annette Kühlem)

An example for the deliberate planting of a palm tree was found within the plaza of the Ahu Hanuanua Mea. Here, a planting pit was carved into the weathered bedrock and filled with garden soil. Within this soil, the marks of the root imprints were found, attesting to the fact that a palm tree was planted in front of the *ahu* and formed part of the ritual architecture of ARUTH.

The palm grove in the central area of the site shows that the palm trees were an integral component of the architectural ensemble and the transformed cultural landscape (cf. Kühlem et al. 2019). The ^{14}C-dates for Pavement 3 and the associated palm tree planting pits are 1440–1490 cal AD, 1440–1480 cal AD, and 1420–1470 cal AD (cf. Fig. 19.17; Table 19.1: No. 11–13). Between the late fourteenth century and the beginning of the sixteenth century (1390–1450 cal AD, 1450–1500 cal AD, 1450–1500 cal AD, and 1450–1510 cal AD, cf. Fig. 19.17; Table 19.1: No. 14, 10, 9, 8) the extensive elaborate pavement with the integrated palm trees and the water canals was intentionally covered by a compacted layer of loamy soil. The closeness of the radiocarbon dates shows that the pavement and the installations herein were not used for more than a few decades.

The geomorphological and sedimentological analyses on site showed that the soil had been transported to the area, leveled out, and then compressed probably by repeated trampling. This was done in several steps, where different layers of different material were applied (Fig. 19.8: Layers 1–5). These layers practically

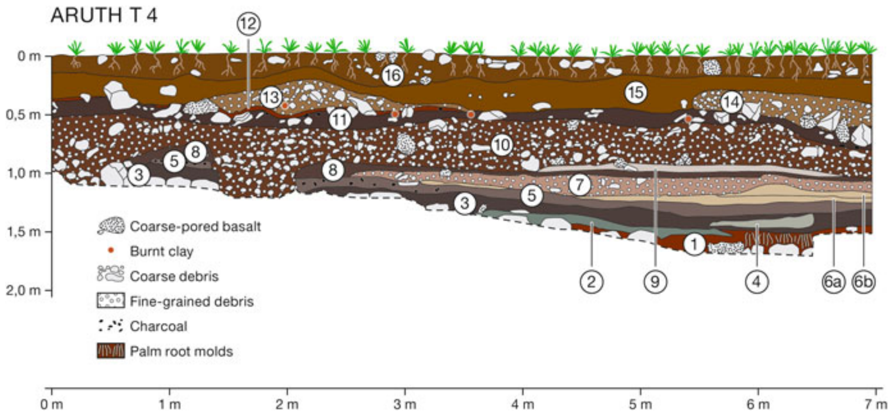

Fig. 19.8 Layers and characteristics of the North-West profile in T4 (field documentation: Annette Kühlem, graphic: Annette Kühlem, Doris Kramer). Layer 1: slightly humic loam with palm roots imprints. 2–5: different applications of sediments that were transported from other cultural deposits to the site and compacted, high content of charcoal. 6–9: body of thin layers of silty material intermixed with fine-grained debris that were deposited by runoff events, 10: thick body of sediment and debris that was deposited during and after a catastrophic flood event. The sorting of the material does not correspond to the natural deposition but shows that it was anthropogenically reworked and leveled out. 11: layer of silty loam that was transported to the site from different cultural deposits and spread out, high content of charcoal and organic material, numerous pits of up to 0.8 m in diameter. 12: powdery humic material that was transported to the site and fills the planting pits in the surface of layer 11. 13, 14: erosion gullies representing singular runoff events. 15: loamy silt deposited by numerous weak runoff events. 16: humic loamy silt deposited by numerous weak runoff events, grass roots, and human-deposited stones in the upper layers

sealed off the underlying pavement and the installations within. It is unclear what happened to the planted palm trees during this process. In some cases, the root imprints inside the planting pits were associated with burnt soil, indicating that at some point the trees in the central area of the site were felled and the stumps burned (cf. Mieth and Bork 2003). There is one example (cf. Fig. 19.8: at 1.4 m to 2.1 m profile length) where a palm tree planting pit was not covered with the compacted sediment. Instead, here the material had been applied around the trunk of the tree.

The eastern water canal (see above; Fig. 19.6) was also still in use after the pavement level had been sealed off by the compacted soil. Some areas of the canal are covered with flat stone slabs, probably to prevent evaporation and/or pollution of the water while the canal still ran at the surface. When Pavement 3 was covered the canal ran underground. In some places along the canal, small shafts were dug into the overlying compacted layer, presumably to clean the canal or to remove blockages. Despite the fact that the pavement and all the installations within were sealed off by the anthropogenic layers there are a few features from the level of Pavement 3 that were still in use.

Excavations in the paved central part of the site were continued in a limited area to investigate the lower levels. Within the 2 x 2 m test pit, approximately 0.4 m

Fig. 19.9 Earliest documented megalithic basin with white sealant around the rim (photo: Annette Kühlem)

below Pavement 3 the rim of an earlier megalithic basin was found (Fig. 19.9). A layer of whitish clay, analogue to that had been found at the base of basin T1, had been applied around the massive stone blocks that make up the walls. Here again, it seems like this material was used as a sealant as it was also smeared into the cracks between the large boulders. The basin has a maximum depth of 1.6 m and the one excavated block in the western wall measures 1.3 m x > 1.4 m. The basin tapers downwards and has a paved floor. Whether this paved floor corresponds to one of the lower pavements that are visible in the embankment profile cannot be said with certainty at this point. The complete dimensions will only be known after further excavations but even at this stage the basin is evidence for megalithic hydraulic architecture in the early phases of the site use.

At some point between 1480–1600 cal AD (cf. Fig. 19.17; Table 19.1: No. 7) a severe flood event descended upon the site of ARUTH (see below). Along with the destructive water mass vast amounts of sediment and rocks were carried down the Vaipú creek. They completely covered the elaborate and labor-intensive installations in the central area of the site with a thick layer of sediment, including rocks (cf. Fig. 19.8: Layer 10, Fig. 19.10). Even the one palm tree (see above) that was still growing was destroyed by this event and the planting pit filled with the sediment that was washed down the creek (cf. Fig. 19.8: Layer 10, between 1.4 m and 2.1 m profile length).

Instead of abandoning the site after such a catastrophic flood event, the ancient Rapanui made use of the fluvial sediment that was deposited in the widening of the valley. On-site geomorphological and sedimentological analysis demonstrate that the matrix of Layer 10 is not entirely naturally deposited but also a product of human

Fig. 19.10 Trench T4 during the excavations (photo: Hans-Rudolf Bork)

activity. The washed in material was anthropogenically relocated and leveled out to form yet another nearly horizontal use-surface. Again, anthropogenic layers were applied on top (cf. Fig. 19.8: Layers 11 and 12). Layer 11 consists of loamy soil with a high content of intermixed charcoal and other organic material. A series of planting pits were found in this layer (Fig. 19.11). The pits were filled with very fine-grained humus sediment (cf. Fig. 19.8: Layer 12) and a multitude of porous rocks. These findings are interpreted as an optimized gardening technique using stone mulching to protect the cultivars from harsh winds and to trap moisture in the planting pits while adding nutrients (cf. Stevenson et al. 1999; Bork et al. 2004). Phytolith analyses are under way. So far, a banana (*Musa sp.*) phytolith from one of the pits attests to horticulture in the late occupation phases in ARUTH (1490–1630 cal AD, 1550–1660 cal AD, cf. Fig. 19.17; Table 19.1: No. 6, 5).

The flood event and the resulting covering of the central area of the site with a thick layer of sediment seem to have brought about a functional and cultural change at the site of ARUTH. The lower levels with the succession of pavements, water basins, canals, and the palm tree grove point to a ritual significance, while the garden pits in the upper levels show a more profane use of the site for horticulture.

Fig. 19.11 Series of later horticultural planting pits in the uppers layer of T4 after the catastrophic rain event (photo: Annette Kühlem)

5 The Stratigraphy of the Southern Embankment of the Monumental Installations of ARUTH (T7)

Trench T7 runs parallel to the Quebrada Vaipú at the western bank of the stream through the former southern embankment of ARUTH (cf. Fig. 19.3). The profile shows the complex stratigraphy of the spacious southern terrace complex of ARUTH. Like in the central area (T4) a sequence of different construction and use phases could be documented (Figs. 19.12, 19.13, 19.14). At the base of T7 there is a body of loose rock debris (Fig. 19.12: Layer 1), the surface of which is covered with a pavement made of slightly weathered small yellowish volcanic rocks (Pavement 1). It is the man-made, water-permeable, former outer wall of the earliest documented terrace at ARUTH. The noticeably yellowish volcanic rocks that had been selected for the pavement possibly had a ritual display function. Above the surface of this earliest terrace lies another anthropogenically deposited layer (Fig. 19.12: Layer 2). It consists of up to 0.45 m of rock debris intermixed with a brown humus fine soil. The surface of this layer is covered by a rough stone pavement (Pavement 2). Layer 3 consists of up to 0.2 m of anthropogenically deposited rock debris intermixed with a brown humus fine soil.

By constructing an embankment (Fig. 19.12: Layer 4), the terrace body of the ceremonial complex was extended by its builders by more than 13 m to the southeast. Layer 4 is a body of rock debris with a trough-shaped, smooth, and carefully assembled surface. In the southern part of this layer, stones with a diameter of up to 1.25 m dominate the matrix. They obviously served to stabilize the downhill part of the structure. In the upper part of Layer 4 the gaps between the large stones

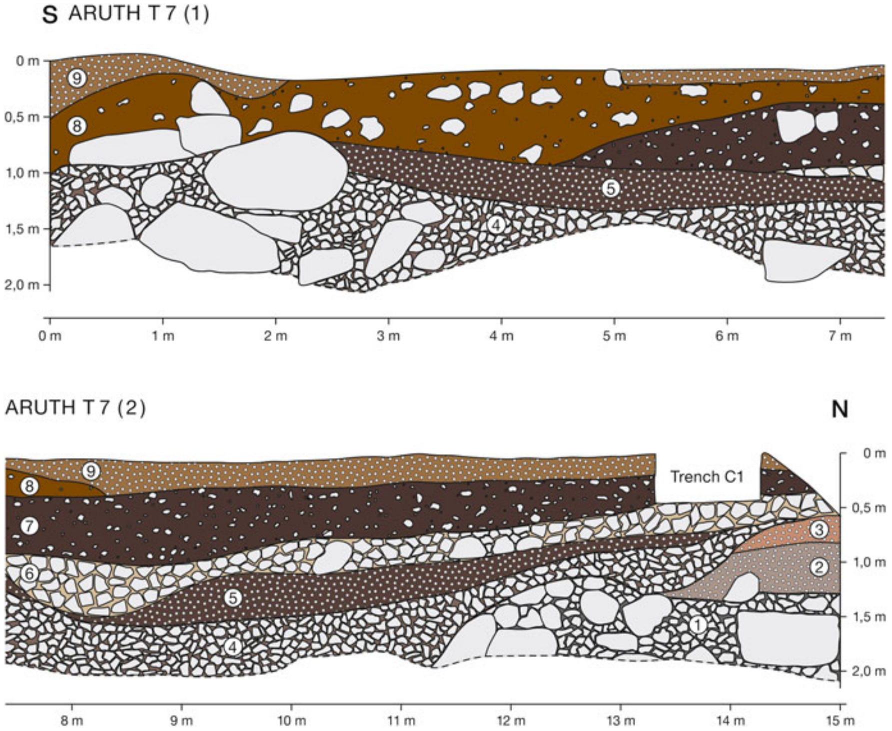

Fig. 19.12 Layers and characteristics of the southern profile in T7 (field documentation: Hans-Rudolf Bork and Andreas Mieth; graphic: Doris Kramer, Hans-Rudolf Bork, Andreas Mieth). 1: loose rock debris with an extraordinary high water permeability with pavement 1 at the surface of layer 1; 2: rock debris intermixed with brown fine soil with pavement 2 at the surface of layer 2; 3: rock debris intermixed with brown fine soil; 4: loose rock debris stabilized with large stones and an extraordinary high water permeability, pavement 3 at the surface of layer 4; 5: rock debris intermixed with brown fine soil; 6: angular rock debris with elaborated smooth pavement 4 at the surface of layer 6; 7: charcoal-rich fine loamy sediment interspersed with small rocks; 8: rock debris with stabilizing stone blocks at the southern rim; 9: brown humic fine sediment intermixed with small rocks; layers 1–9: all deposited by humans

are filled with smaller stones on the seaward side. In the rest of Layer 4 the large gaps between the stones have been preserved to this day. Obviously, the planning of this construction phase involved deliberately leaving gaps between the stones in order to enable the non-destructive subsurface drainage of runoff down the valley. The construction did not serve to retain water, but, on the contrary, had a draining function. The documented profile represents the outer wall of the second oldest terrace profile in T7. A charcoal sample taken from this layer at 3.32 m length of the profile was radiocarbon dated to 1270–1380 cal AD (cf. Fig. 19.17; Table 19.1: No. 16, 17).

Fig. 19.13 View of the southern part of the site ARUTH with profile T7 and the cave in the steep cliff (photo: Hans-Rudolf Bork)

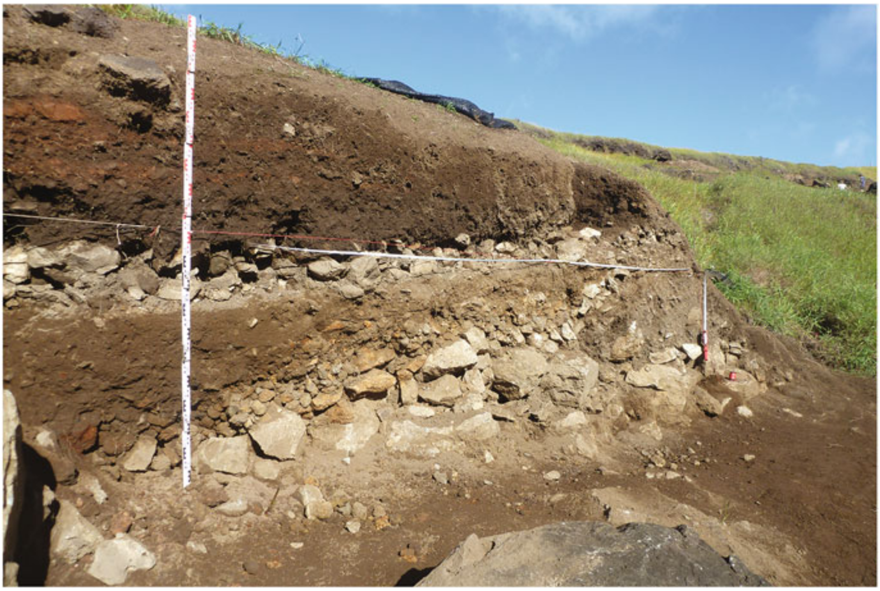

Fig. 19.14 Northern part of the section through terrace complex T7 (photo: Andreas Mieth)

In the central and northern part, Layer 4 consists of anthropogenically deposited, angular stones with a diameter between 0.1 m and 0.3 m. Brown humic sediment with a fine texture lines the cavities between the topmost stones. Layer 4 accordingly forms the stable and deliberately water-permeable outer terrace wall in the southern section of the site. Additionally, it forms the foundation of another elaborate stone pavement further up the creek (Pavement 3).

Layer 5 (Fig. 19.12) is an anthropogenically applied layer of stones intermixed with fine sediment and high amounts of charcoal fragments. A charcoal sample taken 1 cm below the surface of Layer 5 at 10.7 m length of the profile showed a radiocarbon age of 1300–1410 cal AD (cf. Fig 19.17; Table 19.1: No 15). This means that Layer 5 is probably only a few decades younger than Layer 4. Accordingly, Pavement 3 was only in use for a short time before it was deliberately covered with Layer 5.

Layer 6 is made up of angular rock debris broken from larger stones. The surface of it is covered by an elaborate and smooth pavement (Pavement 4). Above Layer 6 lies an anthropogenically applied charcoal-rich layer of up to 0.6 m thickness (Fig. 19.12: Layer 7). The matrix consists of fine loamy sediment with a loose, crumbly texture interspersed with up to 40% small rocks and reddish-brown bands of loam.

Between 0 m and 1.7 m of the profile length Layer 8 consists of stabilizing stone blocks with a diameter of up to 1.1 m (Fig. 19.12). Between and above these there lies a body of rock debris that is rich in fine sediments. Above it a deposit of rough, angular stones forms an extremely stable outer terrace wall. The large cavities between the stones, that were obviously deliberately created by the builders, are still visible today. Evidently this construction layer was also fashioned to reduce the risk of destructive hydraulic pressure. Between 1.7 m and 8.3 m of the profile, Layer 8 is made of rough, angular stones (Fig. 19.12). Between 3 m and 5 m of the profile, the surface is perfectly horizontal, coinciding with the current terrain surface. Layer 9 lies above Layer 8. It consists of brown humic sediment intermixed with small rocks that also forms a nearly horizontal surface (Fig. 19.12: at 5 m to 14.1 m profile length).

Summary of the interpretation: Profile T7 reveals a multi-phase construction and covering of terrace surfaces in the southeastern part of the ARUTH ceremonial complex. Repeatedly, stone pavements were laid only to then be covered again by new terrace constructions. In some cases, the paving was very elaborate with a careful selection of stones according to color. The entire structure does not contain any natural sediments. All layers were intentionally applied demonstrating excellent hydrological and structural knowledge of the builders. The construction shows how the engineers were able to meet the requirements of gravity and hydraulic stability in an outstanding manner by skillfully selecting and combining the materials used. Remarkable is the early beginning of the monumental construction with respect to its location in the island's interior, around 1270 to 1380 AD.

6 ARUTH as a Water Sanctuary

As mentioned above, the most inland *ahu* of the island, Ahu Hanuanua Mea, towers over the elaborate installations of ARUTH. The existence of a ceremonial platform tells us that there was a strong ritual component to the site and that it was under the control of the religious or political elites (cf. Hamilton 2013: 106, Martinsson-Wallin 1994: 129). The single *moai* can be seen as an ideological token of a chiefly lineage, whose power is displayed at the site (cf. Martinsson-Wallin 1994:130). The findings of a crematorium and a stone cist with human remains are evidence that burial rituals were once carried out in ARUTH (cf. Vogt et al. 2018). Water is the defining element at the site and as such was surely intertwined with the funerary rites that once took place there. The outlet at Rano Aroi made it possible to deliberately introduce water into the system of hydraulic installations even during the dry seasons.

Usually, *ahu* are part of a settlement site (cf. Martinsson-Wallin 1994) with remains of house foundations (*hare paenga, hare oka*), cooking pits (*umu pae*), and other manifestations of domestic use. These, along with typical finds from domestic contexts such as food waste or remains of labor tasks such as fishhooks or bone needles, are missing in ARUTH. The few *paenga* blocks that were found in different contexts here all seem to have been taken from other buildings, transported to the site, and used secondarily.

As mentioned above, the availability of fresh surface water did not result in a concentration of settlements along the course of the Quebrada Vaipú. The same is the case for ARUTH itself, where the elaborate hydraulic installations such as canals and basins would have made access to the water even easier. Obviously, the water in the Quebrada Vaipú was not for mundane use and was not available to just anyone. Most likely this is the expression of a taboo relating not only to the site of ARUTH but also to the water in the Quebrada Vaipú. This concept of restricting access to scarce and valuable resources is of utmost importance in Polynesian societies. On Rapa Nui, water was one such scarce resource.

Not only is there no concentration of settlement sites in the vicinity of the water course but the hydraulic installations of ARUTH also did not serve a utilitarian purpose such as the irrigation of crops. There is no evidence for horticulture associated with the canals and water basins.

Comparative research with other Eastern Polynesian islands and the evaluation of sources of oral traditions shed light on the purpose and significance of ARUTH. Water basins are often connected to fertility rituals and/or reserved for elite women (cf. Henry 2004: 545, Douaire-Marsaudon 2002, Ottino 1998: 86, Taaroa 1971: 90, 149). For example, at the site of Puri te Puna on Nuku Hiva in the Marquesas Islands a very similar water basin is known to have been used for ritual baths of elite women after giving birth (Yvonne Katupa, pers. comm.). Here, as at ARUTH, there are petroglyphs on the floor of the water basin, an elaborate pavement covers the ground around it, and a series of trees were planted in the paved area. From other islands, such as Tubuai in the Australs, water basins are known to have been used to discard sacred objects (Aymeric Hermann, pers. comm.). Such objects like tattooing tools, combs, or the like were considered to hold spiritual power (*mana*). To even accidentally touch such objects was considered a breach of taboo and harmful to the mental and/or physical health of the perpetrator (cf. Winthrop 1991: 295).

The fact that at some point the elaborate installations in ARUTH were deliberately covered by compacted layers of sediment, and as such sealed off, also points towards ritual practices. As documented in the stratigraphy of Trench T4 and Trench T7 the ancient Rapanui repeatedly laid extensive pavements, then covered them with sediment, only to lay a new pavement on top. From an engineering standpoint, a practical reason for this is not apparent.

A similar practice has been observed at Ahu Motu Toremo Hiva on the cliff of the Poike Peninsula. There a layer of ground red scoria (*hani hani*) was applied and marks different use phases of the ceremonial platform. As in ARUTH, the material was transported to the site and then spread out (cf. Cauwe et al. 2010).

Another example for a similar sealing of use-surfaces was documented at the Kauri Point site in New Zealand. Here, anthropogenic layers covered a large number of wooden combs that were most likely used to cut the chiefs' hair. Presumably, the sealing layers were applied to prevent that these tabooed objects, that still held the chiefly *mana,* from falling into the wrong hands (cf. Shawcross 1964).

A similar scenario seems likely for the water-related architecture in ARUTH. The fact that there is a repetitive sequence of pavements and compacted layers in a relatively short time frame without any apparent technical reason suggests that the sealing of use-surfaces had a ritual background and was linked to taboos. Possibly, the short intervals between the installation of elaborate pavements and the covering of them is a manifestation of a transfer of power or generational succession.

Rapanui oral traditions describe how in times of drought the high priest was sent to the "highest mountain" (Terevaka) to perform fertility rituals and pray to the God of Rain, Hiro, to bring much-needed rain to the fields. The priest used pigments to paint his face black and white and buried offerings of seaweed and coral that had been soaked in water. The priest continued to evoke the God of Rain until finally "the long tears of Hiro," began to fall. He would then run down the hillside in big circles to make the clouds follow him and bring rain to the fields at the foot of the mountain (Englert 2012). ARUTH is located on the highest mountain of the island, and pieces of coral were found in many of the water-related features at the site. The elaborate installations for the management of water may have been the setting for these rituals that were recorded by Englert.

Over centuries a sacred landscape was created and maintained on the southern flank of the Terevaka. It seems to have served for a fertility cult centered around the site of ARUTH, which was not only a water sanctuary but also a haven for some of the last palm trees on the island.

7 Post-deforestation Pigment Workshops on the Southern Slope of Maunga Terevaka

Pigments played an important role in the cultural history of Rapa Nui. In particular, red and white pigments were used on textiles, stone and wooden artifacts, in the painting of petroglyphs, in the decoration of houses with ritual images, and in body painting. Specific ritual or sacred meanings were assigned to certain colors. For example, the frequently used color "red" was associated with power, spiritual strength (*mana*), fertility, life, and struggle (Lee 1992; Horley and Lee 2012).

So far, there are only a few specific references in the literature in regard to the production technique and local sources of the pigments once used. Even today, the sources of the pigments used for skin painting in the Tapati festival are kept a secret in many families. Many of the island's soils and weathered volcanic rocks contain reddish iron oxides. But the color intensity and especially the texture of the material often do not meet the criteria required for specific and practical application. Thus, the red pigments suitable for ritual use have always been considered particularly valuable because they were only available very locally (Fischer 2005).

The great cultural importance and value of red pigments is exemplified by concentrated deposits of red pigments (ki'ea) in special archeological contexts such as in connection with *ahu* and *moai* (Sherwood et al. 2019; Cauwe 2011). Therefore, recent findings concerning the production and stockpiling of reddish pigments are of particular importance. These findings date to the post-deforestation period and result from geoarcheological fieldwork on the southern flank of the Terevaka volcano and comprehensive laboratory analysis.

Numerous lenticular to u-shaped pits filled with reddish substrate were found at about 240 m asl on the southern slope of the Terevaka in a side valley east of the Quebrada Vaipu. Like the Quebrada Vaipú, its eastern side valley (here named "Vaipú East," cf. Fig. 19.3) only occasionally carries water. The pits, up to 2.4 m in diameter and 0.4 m deep, lie embedded in the sediments of a fluvial terrace (Figs. 19.15, 19.16). A total number of 370 pits were calculated for the entire terrace area, based on the spatial density of 18 excavated pits. Two 7.6 and 5.8 m long profiles showed that the sediments in which the pits are embedded lie above the autochthonous soil with root imprints of palm trees. Sediments and pits therefore date to the time after the palm forest was cleared at this site. Radiocarbon dating of sediments and pit fill from one of the two profiles placed the construction of the pits between 1430 and 1670 cal AD (Table 19.1: 18, 19). In addition, at the base of this profile, a pit filled with reddish substrate from an earlier post-clearance phase was dated to 1220 to 1400 cal AD (Table 19.1: 20, 21) (Mieth et al. 2019; previously modeled dates in Out et al. 2020; recalibrated and modeled dates cf. Fig. 19.17; Table 19.1: No. 18–21).

The main part of the finely stratified pit fillings consists of a silty, reddish substrate of very low bulk density with an average of only 0.58 g cm^{-3}.

Micromorphological and geochemical analyses proved that these reddish pit fill deposits were of geogenic origin and consisted predominantly of the iron

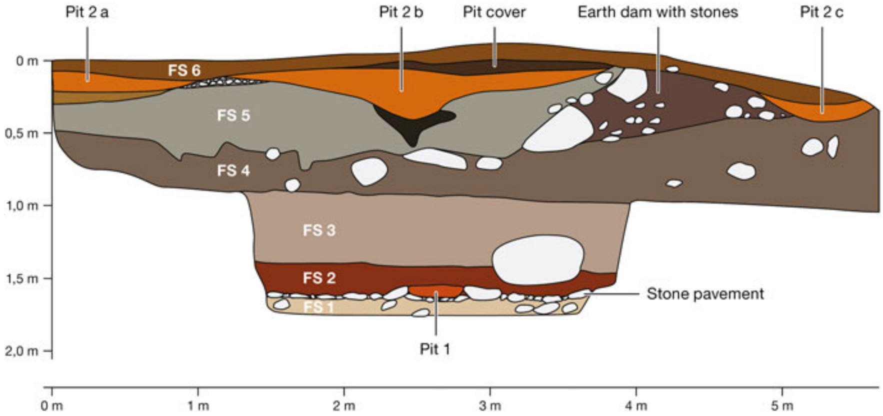

Fig. 19.15 Section from Vaipú East with pigment pits embedded in fluvial sediments (FS) (graphic: Doris Kramer, after Mieth et al. 2019)

Fig. 19.16 Pit filled with reddish pigments from a section in Vaipú East (photo: Andreas Mieth)

minerals hematite and maghemite in very fine and homogeneous grain sizes. The geochemical composition and physical properties of the minerals in the pit fill differ significantly from those of the sediments in which the pits are embedded. Dark brownish to blackish layers embedded in the reddish fill contain concentrations of miniscule flakes of charred plant material. Larger, taxonomically identifiable charcoal fragments were not found. Furthermore, the pit fill deposits contained thin, whitish to light gray layers, which contain a high concentration of phytoliths. The composition of the phytoliths was studied in detail for both the pit fill deposits and the surrounding sediments. While the fluvial sediments are rich in palm phytoliths, the pit fill contains very few phytoliths of palms. Instead, high numbers of grass

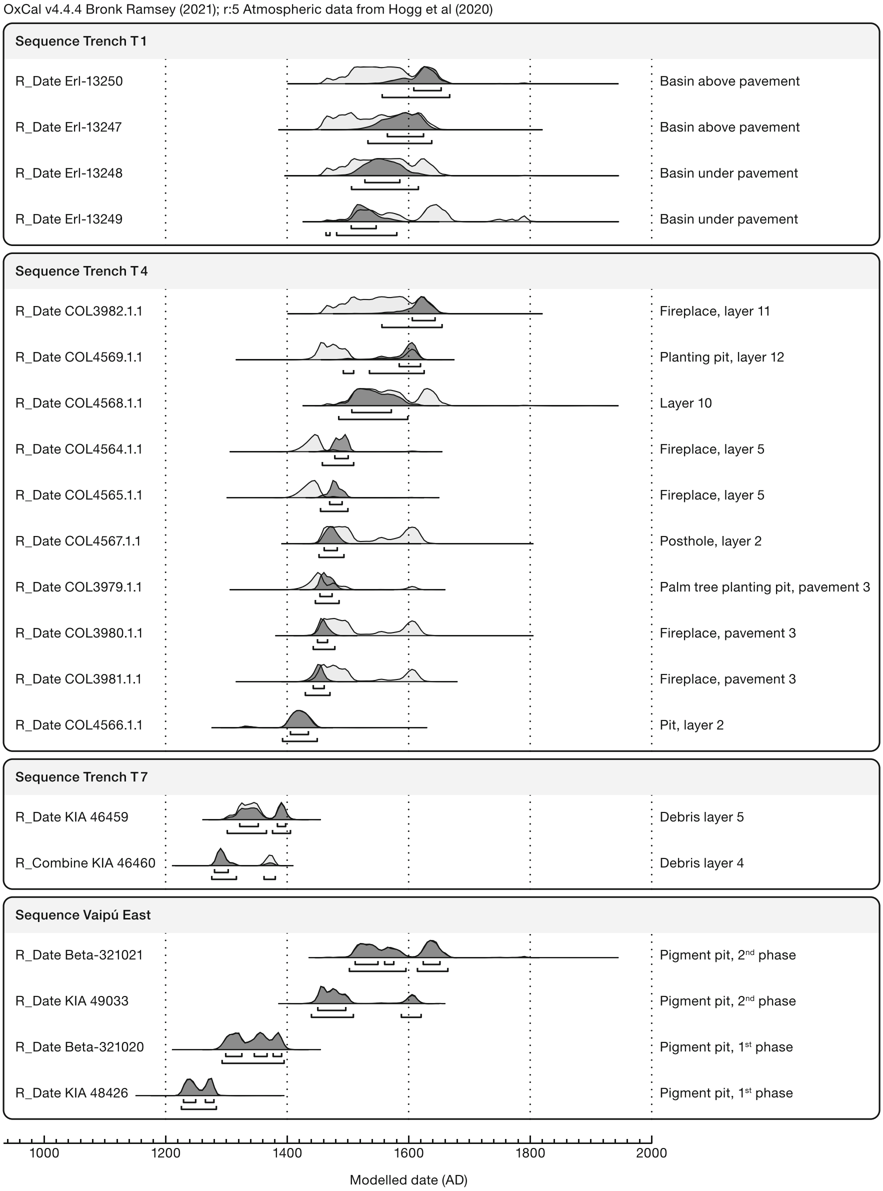

Fig. 19.17 Calibrated ages and OxCal age model of the 14C dates: Calibration and Bayesian phase modeling of the ages was performed using OxCal 4.4 (Bronk Ramsey 2009) with respect to SHCal20 (Hogg et al. 2020). The dates from Vaipú East previously published in Out et al. (2020) and here re-calibrated with SHCal20

phytoliths are concentrated in the whitish-gray layers. Some of the pits are covered with man-made covering layers up to 10 cm thick. These “lids” consisted of a silty loam, brownish substrate.

The following conclusions on the genesis and function of the pits could be derived from these findings. After forest clearing, the runoff of several heavy rainfalls created fluvial deposits in the widening of the valley of the Quebrada Vaipú and its eastern side valley. These fluvial deposits were used for the creation of pigment workshops where pits were dug for the purpose of producing reddish pigments. The geogenic, iron-rich substrate was probably ground to a fine and uniform grain size after its extraction. In an iterative process, single layers, each not exceeding a few centimeters in thickness were placed into the pits and heated by fire. The initially dominant yellowish iron mineral goethite was thereby oxidized to reddish hematite. Grasses served as fuel—presumably the only fuel of which sufficient quantities were still locally available after the forest clearance. The minimal vertical penetration of heat generated from the short-lived grass fires required the mineral raw material to be brought in and heated in numerous steps (layers)—a very elaborate process. Once the pits were completely filled the valuable content was preserved by a human-made sealing and thus protected from wind and water erosion (Khamnueva et al. 2018; Mieth et al. 2019; Out et al. 2020).

The intended use of the pigments is still unclear. The very fine, powder-like texture suggests a use on human skin, perhaps in combination with other substances such as sap from certain plants. While many of the pits and their fill deposits have survived untouched to this day, some have been partially emptied and some have been refilled with pigments during the active time of the workshop. The pigment production ended at its peak when the pits were covered (and thus preserved) by a thick fluvial sediment during an extremely strong and disastrous runoff event (see below).

The pigment pits found at Vaipú East are not the only ones on Rapa Nui. The authors also found pits filled with reddish pigments on a ridge about 1300 m west of the Quebrada Vaipú (Vaipú West, Fig. 19.3) as well as in connection with the monumental installations of ARUTH, where they were embedded in the terrace complexes and anthropogenic layers. Further pigment pits were discovered downstream of the monuments of ARUTH. There as at Vaipú East they are embedded in fluvial sediments (Vogt et al. 2018; Out et al. 2020). It is obvious that pigment production and use in the Vaipú area was not only spatially but also culturally and ritually related to the ARUTH installations and was part of the flourishing cultural manifestations of this particular site.

8 The Destruction of the Monumental Installations at ARUTH and the Spillage of the Pigment Workshops by a Flash Flood

Over the centuries, cultural layers and natural deposits accumulated in the widenings of the Quebrada Vaipú valley and in its eastern side valley (Vaipú East). In ARUTH, a succession of three pavements was built (see above). These pavements were divided by a sequence of anthropogenic layers of compacted earth and reworked sediments deposited by strong runoff (see above; Figs. 19.5 and 19.8; Vogt and Kühlem 2017). After the first phase of pigment production at Vaipú East, fine and coarse sediment carried by the runoff from heavy rainfall was deposited layer upon layer in the area of the pigment workshop (see above; Fig. 19.15). Subsequently, the production of pigments at an almost industrial scale began on the almost flat sediment surface (see above).

Then, during the phase of ritual use of ARUTH and the by far most intense phase of pigment production, a presumably completely unexpected catastrophe hit the unprepared people in the Vaipú area: a flash flood of unprecedented proportions irreversibly destroyed both complexes. Water volumes from an exceptionally heavy rainfall cut through many meters of the ritual site of ARUTH, rendering the ritual and hydraulic installations unusable. It seems that this event led to a functional change in ARUTH with no further evidence of ritual use.

In the Quebrada of Vaipú East the torrent of water tore away part of the fluvial sediment deposits together with the carefully covered pigment pits. On another part of the sediment body, slightly rounded gravel was deposited at the end of the flash flood resulting in an up to 1 m thick stone layer. The largest deposited stones weigh up to around 200 kg, showing the force with which the water came down the Quebrada during this catastrophic event. This youngest sediment layer protected the remaining older sediments of the pigment workshop from further erosion until today.

An undated legend that is directly linked to the toponym of the ARUTH describes the dramatic effects of such a flash flood. Ko te Ava Ranga Uka a Toroke Hau is translated as “Place where Uka, the daughter of Toroke Hau, floated in the stream.” The legend describes how one night her parents left Uka alone at home to attend a feast. While they were gone, a heavy flash flood washed away the house with the sleeping girl. Upon their return Uka’s parents found her lifeless body floating in the stream. In remembrance, the place where she was found was named after this tragic incident (Englert 2012).

What caused this catastrophic event? Why had the Rapanui not taken any precautions to protect themselves from such a disastrous event? What role could land use have played for such an event to occur? In the centuries after deforestation and before the main pigment production started, the garden soils in the Quebrada Vaipú catchment had been largely eroded (Mieth and Bork 2015, 2017; Mieth et al. 2019; Bork et al. 2019b). As a result, solid volcanic rocks, which were previously covered by the soils and were barely weathered, came close to the surface in many locations. The erosion of the soil greatly reduced the infiltration capacity. As a result, frequent moderate rainfall was enough to cause runoff, which further eroded the remaining soils and deposited the eroded soil particles in the valley floor and in the sea. Subsequently, during the period of intensive pigment production, a considerable part of the grass vegetation which had developed in the catchment area of the Quebrada Vaipú after deforestation was apparently needed for the complex pigment production process. As a result, the soils lost any erosion protection. This led to a cumulative effect of the now very low infiltration capacity of the remaining soils and the volcanic rocks with the lack of erosion protection provided by vegetation. The combination of both factors enabled the devastating and simultaneous destruction of the ritual site of ARUTH and the pigment workshops during one exceptionally heavy rainfall event. The Rapanui had no chance to prevent this catastrophe. After the extensive erosion of the soil and the removal of the grass vegetation cover, such an event was inevitable. It was just a question of time.

9 Synthesis and Conclusions

The research presented here shows that forest clearing on the southern slope of Maunga Terevaka at an elevation around 240 to 275 m asl and about 5 km from the coast had already begun before ca. 1220 to 1290 AD. This is further evidence that already at this time at least parts of the highlands were affected by intense human activities. And this in turn is another link in the chain of evidence that around 1200 AD Rapa Nui must have already been populated by a larger population.

Forest clearing on the southern slope of Maunga Terevaka was followed by cultural activities that are unique for Rapa Nui. Along the Quebrada Vaipú and especially at ARUTH, people erected monumental hydraulic installations and terraces. These constructions dominated the drainage valley of Lake Rano Aroi, crowned by the most inland image *ahu* of the island. At ARUTH, the islanders transformed the landscape in ways that are without parallel on Rapa Nui. The oldest part of the terrace complex has been dated to ca. 1270 to 1380 cal AD! early cultural dates for Rapa Nui's highland region.

The monumental structures at ARUTH are not single phased constructions. Over generations, the terraces with their elaborately paved surfaces were sealed with artificially applied layers of sediment, covered with new paved surfaces, then built-over again, and in the process also expanded in surface area. In the end, the monumental complex extended over a total area of at least 4800 m^2. This is the largest architectural complex known on Rapa Nui to date and proof of an enormous amount of labor that was invested here over at least 15–20 generations. An outstanding finding is the evidence of planted palms in the plaza of Ahu Hanuanua Mea and the small palm grove amidst the pavement in the central area of the site. They date to a time when palms had already disappeared or had at least become scarce in the surrounding landscape. The *ahu*, the site's location in the island's only water-bearing valley, the findings of carefully constructed megalithic basins and canals, the palm planting, and the absence of ordinary settlement structures all point towards a ritual use as a water sanctuary. There is much evidence to suggest that the water of the Quebrada Vaipú, as a scarce and valuable resource, was placed under taboo with its management and use reserved for the elites. Comparative studies on other East Polynesian islands and oral traditions of the Rapanui support this.

During the dry season, the flow of water in what now appears to be a largely dry valley was not left to chance. An artificially created outlet dug into the weathered rock at the southern edge of Lake Rano Aroi enabled the ancient Rapanui to control and manage the flow of the water. In turn the stability of the loosely fitted stone layers in the terraces ensured a non-destructive outflow of the water after passing through the sacred installations at ARUTH. The monumental constructions prove that the Rapanui were not only excellent structural engineers but also knowledgeable hydraulic engineers. Such hydrological knowledge as part of landscape transformation is a new aspect of Rapanui cultural expressions, as is the existence of a water-related fertility cult. The findings described here may also shed new light on the results presented by DiNapoli et al. (2019) regarding not only the spatial coexistence, but perhaps also ritual connection of coastal *ahu* and coastal water sources on Rapa Nui.

In the eastern side valley of the Quebrada Vaipú, intensive production of reddish pigments began around the same time as the installations at ARUTH after the clearing of the forest around 1220 to 1290 cal AD. The pigments were produced by burning ground minerals using large quantities of dry grasses as fuel. A considerable amount of labor was required for this pigment production on an industrial scale.

After the forest clearing, many generations of Rapanui successfully managed stronger runoff events in the catchment area of the Quebrada Vaipú and its eastern tributary valley. At ARUTH material from fluvial deposits was deliberately used in the construction of the monumental terraces. At Vaipú East, pits for pigment production were specifically integrated into the fluvial sedimentary bodies. However, progressive soil erosion following the loss of the palm forest and then the gradual destruction of even the protective grass vegetation due to the demand for fuel in the pigment production increased the risk of an extreme runoff event. Such a catastrophic, once-in-a-lifetime event occurred in the period between 1480–1600 cal AD. This runoff event cut through and destroyed a significant part of ARUTH's monumental structures and simultaneously ended the pigment production at Vaipú East. Although this event probably meant the end of ritual activities in ARUTH, it did not mean the complete abandonment of the site. Horticultural activities in the upper sedimentary layers provide evidence of continued use of the site, albeit of a horticultural nature.

The findings on the southern slope of Maunga Terevaka are an important component in the reconstruction of the cultural history of Rapa Nui. They attest to the early beginnings of an active, ambitious, and extremely industrious culture with a strong ritual component after the clearing of the palm forest. They provide evidence of the persistence of extremely labor-intensive and skilled engineering over many generations. They provide evidence of the persistent adaptation of cultural activities to the natural challenges of the island ecosystem and man-made environmental changes. They do not, however, provide evidence for a post-deforestation collapse of the Rapanui culture in pre-European history.

Acknowledgements Our research would not have been possible without the assistance and friendly cooperation of a many institutions worldwide. We, therefore, wish to thank the Consejo de Monumentos Nacionales (Santiago), the Comisión Asesora de Monumentos Nacionales (Hanga Roa), Ma'u Henua (Hanga Roa), the Secretaría Técnica de Patrimonio Rapa Nui, the Consejo Nacional Forestal (Hanga Roa), the Mata Ki Te Rangi Foundation (Hanga Roa), the Museo Antropológico Padre Sebastian Englert (Hanga Roa), the Universidad de Playa Ancha (Valparaiso), the Musées Royaux d'Arts et Histoire (Brussels), the HafenCity Universität Hamburg, the Fachhochschule Köln, the University of Otago, and the Max Planck Institut Jena. We owe special thanks to Sonia Haoa Cardinali for all her help and advice, to our local cooperation partners, Francisco Torres-Hochstetter and José Miguel Ramirez, to our foreworkers Sorobabel Fati Teao†, Singa Pakarati, Neka Atan Hey, and Pelayo Tuki, to our supervisor Edmundo Pont Chavez, as well as to Merahi Atam Lopez, Roland Botsch, Claudia Bührig, Vittoria Buffa, Nicolas Cauwe, Sophia Dazert, Moana Edmunds Gorman, Jörg Faßbinder, Christian Hartl-Reiter, Werner Herberg†, Aymeric Hermann, Isaias Hey Gonzalez, Anja Igelmann, Tikitehau Ika, Peter Im Obersteg, Felix Jasiak, Thomas Kersten, Peter Kozub, Doris Kramer, Maren Lindstaedt, Friedrich Lüth, Justin Maxwell, Klaus Mechelke, Johannes Moser, Catherine Orliac, Mahina Pakarati Trengóve, Francisca Pakomio Villanueva, Sheba-Celina Schilk, Nikolaus Schlüter, Werner Schön, Kristin Schreyer, Joaquín Soler Hotu, Alan Tepano, Monica Tromp, Vaihere Tuki Haoa, Ingmar Unkel, Miriam Vogt, Kai Zabel, and all our wonderful local excavation workers who over the years contributed to the success of the project. Maururu.

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Chapter 20
Ecology Limits Population, But Interaction with Culture Defines It: Carrying Capacity on Rapa Nui

Cedric O. Puleston and Thegn N. Ladefoged

> *Quantifying the unquantifiable is sometimes a necessary academic practice, but it is justifiable only if the essentially artificial nature of the exercise is never forgotten.*
>
> *–Tim Bayliss-Smith (1980: 62)*

1 Introduction

The study of island populations allows us unique insight into the relationships between human behavior and the environment. As Kirch (2007a) and others have pointed out, the Pacific represents a marvelous natural experiment because large parts of it were rapidly settled by descendants of a common founding population, bringing with them similar beliefs, agricultural practices, and technology. But despite the common origin of Polynesia settlement, by the time of European contact there was (and still is) tremendous diversity in population density, socio-political organization, the extent of inequalities and social stratification, diet, and the nature of daily life. This variation in response to variable environmental conditions holds the promise of deep insight into the study of human history, evolution, and ecology.

Importantly, one of the key elements in this natural experiment, the quantification of population, remains elusive. There are no detailed written census records from before European contact. In their absence, we can break the study of traditional Polynesian populations into three distinct phases: first-hand European observa-

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_20

tions, second-hand knowledge, and the modern effort. First-hand observations of European visitors varied widely in their quality. Some simply recorded general impressions, while others attempted a more systematic estimate of the population numbers at the time of their arrival. Many of the most careful observations were made by members of the expeditions led by Capt. James Cook as they met with people from numerous islands across the Pacific in two voyages. In general, European observers were surprised by the size, and in some cases, wealth, of the populations they encountered. Johann Reinhold Forster, a naturalist on Cook's second Pacific voyage, was much impressed by the crowd that greeted the expedition's ships off Tahiti, and he used his counts of participants, along with estimates of the length of the coast and the productivity of sample breadfruit trees, to conclude that 121,500 people might live there (Forster 1996 [1778]). Cook's Lt. James King estimated 500,000 people lived on the Hawaiian Islands based on extrapolation of the population along the coastline (Beaglehole 2017), a number he later reduced to 400,000. Lt. William Bligh estimated 242,200 people without explanation of his reasoning (ibid.). This first informational phase is characterized by the observations of alien visitors, who often reported being surprised at the large population densities they encountered, but with limited opportunity to observe the interior and having no opportunity for a systematic survey of population.

The second informational phase centers around the early censuses of Christian missionaries who followed the whalers and traders, arriving decades after first contact to spread their religion and quantify the number of souls that might be saved. These earliest systematic accounts paint a dramatically different picture. Across the Pacific population densities are quite low, with evidence of abandoned homes, villages, and agricultural land. There are some accounts of the way life had been around the time of European contact (e.g., Malo 1951 and I'i 1959), but by the time these accounts were recorded all aspects of Polynesian society had undergone tremendous change. Population was much reduced by deadly diseases brought by the Europeans, and sexually transmitted diseases further reduced the fertility rates of the survivors for generations. By some estimates, populations were reduced by as much as 95% within decades of contact (see Stannard (1989) and Rallu (2007)). In the 1830s, one observer lamented that "the Sandwich [Hawaiian] Island race is fast diminishing, in but a few years it is to be feared that they will be spoken of as a people that were, but are not" (Rooke 1838).[1]

Modern scholars find themselves in the third informational stage, with direct observation no longer possible and those who witnessed the immediate aftermath of contact long gone. Beyond the records of the earlier two phases, we are left with two main resources to understand what life in Polynesia might have been like at the cusp of European contact. These sources are (1) the discovery and interpretation of information about that era, including evidence of residential occupation, economic activity, and land use, as well as information gathered from human remains, and

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[1] Quoted in Dye (1997).

(2) the characterization of agricultural and economic potential, given its cultural and ecological context, with the goal of estimating some measure of the number of people who might have been able to live in a place under a particular set of assumptions.

This third phase has been defined by a debate that has endured for multiple generations of researchers. It has its beginnings in the work of Norma McArthur, a demographer, who argued that the first careful records available to us, via the early missionary reports, suggest that the precontact populations were relatively small, even accounting for some effect of introduced disease, and that the observations of the first European visitors were likely gross overestimates of the actual populations (McArthur 1967). McArthur's view became the dominant one, and it took a new generation of scholars to begin the process of overturning it. Jean-Louis Rallu (2007) recounts how in 1989 his Ph.D. defense jury insisted he include only the lower bounds of his estimates of Tahiti's population if he wanted to pass. Similar battles were fought over population estimates in the Americas.[2] Rallu regards the reluctance of Western scholarship to recognize and accept the possibility of dense settlement in the Pacific and the Americas as a vestige of colonialism. Kirch (2007b) describes the difficult unraveling of McArthur's position in the Pacific, led by David Stannard's (1989) examination of the Hawaiian Archipelago and the population it might have supported when Cook first arrived. Stannard argued that Lt. King's estimate of the population was probably too conservative and based on evidence of land use and mariners' accounts that there may well have been 800,000 or more people living on the islands in 1778. In the decades since there has been some effort to confront McArthur's legacy, led in no small part by the growing number of indigenous Polynesian scholars. It has become more generally accepted that McArthur underestimated the true numbers, but there is no consensus as to the magnitude of the error. Our aim here is to address a number of these shortcomings and consider a framework by which we might incorporate ecological data into our estimates of ancient populations. In this chapter we describe how environmental and social factors influence human population and then move to an examination of two modeling approaches that incorporate these elements into estimates of maximum population size. We adopt Rapa Nui (Easter Island, Chile) as a case study, parameterizing the two models for the island and comparing the results to previous estimates of its population.

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[2] The father of one of this chapter's authors, archaeologist Dennis Puleston, was presented with an almost identical demand by his Ph.D. committee to reduce his estimates of the population of the Maya city of Tikal some 20 years earlier. A draft of the dissertation with the handwritten comments from his committee is available in his papers at Princeton's Firestone Library (http://arks.princeton.edu/ark:/88435/br86b3627).

2 What Limits Polynesian Populations?

One aspect immediately apparent to anyone interested in studying the past or present of Polynesia is that there was and is tremendous variation in population size and density from island to island. Land area is not a particularly good predictor of population, suggesting that there are multiple drivers at work. If one wanted to make a prediction about population on one of these islands at the point of European contact, what information would be most useful? Despite our uncertainty about exact population sizes, a few discriminating questions emerge. Is the island an atoll, a high volcanic island, or continental in nature? The first is made up of a coral cap atop what was once a volcanic island that has since submerged. Its soils are calcareous and generally poor. Crops are either rain fed or rely on access to the freshwater lens that usually lies below the ground of atolls, creating productive swampy areas in some. High islands are characterized by volcanic soils which, depending on their age, may be a good source of essential rock-derived nutrients. They are also likely to experience greater rainfall and more likely to feature seasonal or year-round waterways appropriate for irrigation. Islands of the continental type are characterized by more complex geology and may host a wider variety of endemic species than the previous two types. It might also be useful to know something about the climate where the island is located. Is it more temperate, like Aotearoa New Zealand, where some Polynesian staple crops can only grow in parts of the archipelago in parts of the year, and many staples do not grow at all? Or is it tropical, like Tahiti in French Polynesia? How much rainfall does the island receive?

All of these questions get at the *resource potential* of an island: the availability of land suitable for the important cultigens of taro, sweet potato, breadfruit, bananas, and coconut. They also tell us something about the availability of animal protein, including the fish and shellfish found in greater abundance around atolls, and terrestrial domesticates, which may be more likely to thrive on the bigger high islands.

It seems reasonable that access to food resources might limit populations on islands and elsewhere, but how do we generate a model, or equivalently, a set of general principles by which we might estimate the greatest number of people who might have lived in a particular place? One approach, and perhaps the most deeply entrenched, is to focus on the availability of carbohydrates, which are fundamentally important to the Polynesian diet. Tim Bayliss-Smith (1974) did a careful study of several Polynesian Outliers near the Solomon Islands in the early 1970s. He was interested in the question of population limitation and chose the location because the islands were relatively isolated (“closed”), the inhabitants still ate essentially a subsistence diet, and the imported foods that they consumed were arguably simple replacements for traditional diet items. He suggests that although population on these atolls was self-regulated by “cultural controls” (including abortion and infanticide) as opposed to starvation, the desirable population levels were informed by food availability. In other words, resource limitation created an upper bound that the islanders were aware of and worked to avoid.

But food is more than just calories. What is acceptable as a diet varies across time and space and people may suffer hunger in the presence of plenty if the resources do not meet their definition of edible, or if the food cannot be balanced with other resources considered essential. Echoing observations made elsewhere in Polynesia, Bayliss-Smith (1974) writes that going very long without taro (a starchy root crop of particular importance across the Pacific) “is considered a great hardship,” and that of all the foods available, the starchy tuber is “the main determinant of the maximum carrying capacity” for cultural reasons as well as for its caloric density and return to labor inputs. He defines “carrying capacity” as “the ceiling to population growth that the ecological constraints in a given system of resource management determine,” by which he means a maximum population in a specific agricultural and technological context. Unlike taro, coconut appeared to be available in surplus on these islands, despite its favorable caloric density and return to labor inputs. In three surveys of diet and food resources on the atolls, he found that although diet composition changed across time and space, taro and its substitutes made up a minimum of 30% and maximum of 70% of the caloric input, and averaged close to 50%. Coconut was 15–20%, and fish 10–30%. As plastic as the diet was, there were bounds of acceptability that appeared to be defined as much by culture as nutrition. These populations desired some 50% of their calories to come from taro and other starches, but 25% represents the “extreme limit of acceptability.” Bayliss-Smith acknowledged that dietary preferences might have changed since precontact times, but felt justified in using these findings as the basis for his analysis.

To estimate carrying capacity, Bayliss-Smith calculated the area available for the two dominant taro varieties grown on the atolls. Some of these areas were not in use for taro or even at all at the time of his study, but he believed they likely were used in the precontact era. Using local yield estimates he calculated the maximum sustainable population based on the total productivity and the minimum consumption level of each of the two staples. This food output was divided by the mean energy requirement per individual, which was estimated at 1800 kcal/day after considering the population structure and several studies of energy consumption.

On two of the atolls “overcrowding became a perceived reality when numbers were only 70–80% of the maximum carrying capacity” (Bayliss-Smith 1974). Bayliss-Smith found that expressing population density as a function of agricultural area (taro-suitable area in this case) made more sense than using total land area (see Kirch (2010) and others for later applications of this approach). He also found that population density (in the 1970s) was negatively correlated with atoll size across a larger sample, but that may well have been because a number of the larger atolls in the comparison were drier and were less agriculturally productive as a result. In any case, Bayliss-Smith cautions against using his data and findings to make more general statements about Polynesian populations on atolls. His results hinge on the agricultural area and productivity of the staple foods, and Bayliss-Smith warns that the analysis should not be ventured upon without reliable local data. And although he finds a relationship between the carrying capacity calculation and modern and past population estimates, he emphasizes that in some places periodic natural disasters may keep populations below this threshold, or induce the population to manage its own numbers to mitigate the risk of famine.

The three food categories Bayliss-Smith (1974) examines, taro, coconut, and fish (and their substitutes), map well onto the three major macronutrients in the human diet: carbohydrates, fats, and proteins, respectively. These are important sources of energy, and are often important sources of other essential micronutrients. Modern health experts suggest that the acceptable macronutrient distribution range (AMDR) is 45–65% of total calories from carbohydrates, 20–35% from fat (for ages 4+), and 10–35% from protein (for ages 18+) (Institute of Medicine 2005). However, there are examples of populations that have existed for long periods on diets that do not meet these requirements, including the Inuit of extreme North America and the Moriori on Rēkohu (Chatham Islands, Aotearoa New Zealand), both of whom consumed considerably less carbohydrate than the AMDR, replacing much of it with the blubber (fat) of marine mammals (Leach et al. 2003).

That fat and carbohydrate might be exchanged for one another raises the question of protein. Protein is made up of amino acid building blocks, which our bodies may break down and use in our own metabolic machinery to make new proteins for our own use. However, there are a number of amino acids deemed "essential" in that our bodies are unable to manufacture them and so we must acquire them from proteins in our diet. Even in the presence of an abundance of fat and carbohydrate, a shortage of these essential amino acids will lead to hunger, wasting as the body breaks down muscle tissue to free up amino acids, and finally death.

In response to Bayliss-Smith (1974), anthropologist Stephen Beckerman was interested in whether access to protein might limit population sizes on the high islands of the Pacific, because in comparison to the atolls Bayliss-Smith studied, these islands supported a greater variety of food sources, and because there seemed to be arable land that lay uncultivated, as if available in excess (Beckerman 1977). The idea of protein limitation on population growth had been proposed for the Amazon, and although Beckerman was skeptical of its applicability there, he thought it might make more sense in the Pacific. He proposed that if coconuts and reef fish were the main sources of scarce protein, and these were concentrated along the shore of most Polynesian islands, then maximum subsistence population should correspond to island circumference. He gathered shoreline length estimates for 10 Polynesian high (volcanic) islands representing a range of sizes and used estimates of population size at the time of European contact, all generated in the previous 10 years to reflect the post-McArthur revisions then underway. He plotted the population estimates against the shoreline length and performed a linear regression. He reported a correlation coefficient of 0.967, and the resulting equation predicted that once a minimum threshold was met (approximately 50 km), each kilometer of shoreline supported 222 people. A plot of population vs. area did not show a strong linear relationship, encouraging Beckerman to conclude that shoreline-associated protein sources were indeed limiting.

Citing their observations from Micronesia, Rosalind Hunter-Anderson and Yigal Zan responded that the protein limitation hypothesis did not explain what archaeologists and anthropologists were finding on Yap and its surrounding island complex

(Hunter-Anderson and Zan 1985). They argued that Beckerman's analysis did not stand up to closer scrutiny. First, they pointed out that the Yap Island Complex probably supported two or more times as many people as Beckerman's equation predicts, based on house counts. And Yap is a perfect candidate for a fish-dependent population, being surrounded by a rich lagoon, unlike the islands in Beckerman's analysis. They argue that despite the presence of a correlation in Beckerman's data, shoreline extent is not necessarily an indicator of protein availability in the diet. In the Hawaiian Archipelago, the seven islands showed only a weak relationship between reef length and shoreline length ($r = 0.101$), and the islands with the largest populations in the study (the geologically younger Hawai‘i and Maui) had less reef. In addition, areas of known population concentration in the precontact era did not correspond well with reef zones for five out of the seven islands in the chain. The authors also cite evidence that coconut was not an especially important part of the diet among the Hawaiians. The correlation Beckerman observed could be explained just as easily by factors related more closely to agricultural potential, including the presence of soils suitable for rain-fed and/or irrigated agriculture, or the presence of brackish swampy areas suitable for the production of starchy staples often found at the edges of volcanic islands.

Hunter-Anderson and Zan proposed the more general "intensification hypothesis": "the upper limit of population size appears to be conditioned by the presence of intensifiable resources. Under certain geographical conditions, these resources might involve protein, and under others, starch. In small tropical high islands, the intensifiable resources tend to be starchy" (Hunter-Anderson and Zan 1985:63). Accepting Beckerman's proposed relationship between island perimeter and population, they found that perimeter was in fact a better predictor of terrestrial resources (land area) than marine resources (reef length) among islands in the Hawaiian Archipelago. They found strong relationships between perimeter length and the (1) extent of replaced-vegetation cover, (2) area of swampy brackish water, and (3) area of all intensifiable soils. Further, they point out that Beckerman's model is inapplicable to islands smaller than 50 km circumference runs counter to the protein hypothesis as well. These small islands are mostly coral atolls, and it would be reasonable to expect these populations would be most closely tied to resources from the sea. The intensification hypothesis is a better explanation of population limits on these coral and limestone atolls: "In these settings intensive taro cultivation is possible due to the subterranean fresh water lens which is thickest towards the centre of the island. Accordingly, taro gardens tend to be located in the centre of coral islands rather than on their peripheries, which are either rugged reef rock or excessively drained beach sands" (Hunter-Anderson and Zan 1985:64).

3 Carrying Capacity

Each of the studies we have examined so far is an attempt to describe "carrying capacity," whether numerically, as in the case of Bayliss-Smith (1974) and Beckerman (1977), or in more general terms (Hunter-Anderson and Zan 1985). A key moment on the path to the modern concept of carrying capacity occurred when mathematician Pierre-Francois Verhulst (1977 [1838]) derived an equation that seemed to capture important aspects of how populations grow to their maximum density. All one needed to know was the maximum growth rate, r (assumed to exist when the population was infinitesimally small), and the maximum population size, K. The growth rate at any point is determined by the equation:

$$\frac{dN}{dt} = rN\left(\frac{K-N}{K}\right),$$

where N is the population size and t is a measure of time. Verhulst's equation imagines a population whose per capita growth rate is unfettered when the population is small and resources are abundant, but each new individual draws down those resources and thus reduces the growth rate going forward. There are only enough resources to maintain K individuals, so as a population approaches K, which later came to be termed the carrying capacity, the balance of its birth and death rates get closer and closer to zero. Although the equation does capture the dynamics of some populations, it has a checkered history in the study of humans. Despite both its potential utility and the inherent reasonableness of the idea that resources are finite and populations that subsist on them should be, too, "pragmatic and conceptual problems bedevil attempts to calculate human carrying capacity, and this simple cybernetic model has been left without effective application. This has led to redefinition, to circumlocution, and, finally, to denials that such a thing exists" (Dewar 1984:601).[3]

Dewar (1984) argued that we have often confused two related concepts in our thinking on carrying capacity. The K described by Verhulst is a demographic construct, based on how the growth rate responds dynamically to population density. This should be separated from what some have called the ecological, or environmental, carrying capacity, which can be defined as "the maximum ability of an environment to continuously provide subsistence at the level of culture provided by the inhabitants" (Hayden 1975:11). Others have identified an additional host of uniquely human variables that would further reduce maximum, or equilibrium, populations from the environmental carrying capacity. This has been called the social or cultural carrying capacity, defined as "the maxima that could be sustained under various social systems" (Daily and Ehrlich 1992:762). Or, as Seidl and Tisdell (1999:403) put it:

> The application of carrying capacity to the human species requires the recognition that the carrying capacity is foremost socially determined, rather than biologically fixed due to the important influence of human consumption patterns, technologies, infrastructure, and impacts on the environment or food availability.

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[3] Similarly, Tuljapurkar et al. (2007:37) called carrying capacity an "intuitively appealing if slippery concept."

Human populations affect their food resources through exploitation (and over-exploitation) of wild foods. We also have the ability to develop new food production practices and technologies, which in Polynesia included the development of more efficient fish hooks, selecting for better cultivars, constructing fish weirs and ponds, investing in agricultural infrastructure (e.g., irrigation systems, stone mulching, or linear alignments or walls for windbreaks), or environmental engineering to modify geomorphological settings, and other forms of niche construction. To make generalizations even more difficult, human culture may lead to choices about food and other resources that vary across time and space, requiring the consideration of cultural attributes. Examples of these choices, or behaviors, include the degree of social stratification and expected amounts given in tribute, the degree to which individuals and neighboring communities cooperate or engage in hostilities with one another, the sexual division of labor, the presence of formal or informal methods of fertility or mortality control, the degree of agricultural intensification, and diet composition. There is also the issue of the time period that individuals are considering in their decisions about subsistence production and the likelihood of "good" or "bad" years within that time period. The sad truth is that any estimate of human carrying capacity must make assumptions about all of these things, and more. These difficulties do not invalidate the practice, but we would be wise to expend the effort to understand the ones that are most likely to affect our results. In the next sections, we will consider the role a number of these factors play in two models of population size parameterized for the island of Rapa Nui (Easter Island, Chile).

4 Considering Human Welfare, a Rapa Nui Case Study

When the Dutch explorer Jacob Roggeveen's ships became the first European vessels to arrive at Rapa Nui in 1722, he made two relevant observations in the ship's log. The first was that the population had every appearance of health: "These people have well proportioned limbs and large and strong muscles; they are big in stature . . . . These people also have snow-white teeth with which they are exceptionally well provided, even the old and hoary, as was evidenced by the cracking of a large and hard nut, whose shell was thicker and more resistant than our peach stones" (González 1903:15).[4] This appraisal of the health and robustness of the islanders was echoed in the notes of other members of Roggeveen's party and is supported by modern research.[5] The second observation was that the island appeared to be well suited for agriculture, even if it was not being used at its full capacity:

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[4] An excerpt of Roggeveen's lost and rediscovered ship's log was translated into English and published in the Hakluyt Society's series on great explorers in a volume, along with the account of the second known visit to Rapa Nui by a European, Don Felipe González's 1770 landing.

[5] A study of the remains of 125 Rapanui who died in the contact era lends credence to Roggeveen's observations. Biological anthropologist Caroline Polet (2006:269) concluded that analyses of the bones and teeth "indicate a relatively good state of health among the Rapanui during

> [W]e found it ... exceedingly fruitful, producing bananas, potatoes, sugar-cane of remarkable thickness, and many other kinds of fruits of the earth; although destitute of large trees and domesticated animals, except poultry. This place, as far as its rich soil and good climate are concerned, is such that it might be made into an earthly Paradise, if it were properly worked and cultivated; which is now only done in so far as the Inhabitants are obliged to for the maintenance of life (ibid., p. 21).

This description of hearty Rapanui with pearly white teeth stands in stark contrast to the sad, rotten-mouth natives described in Jared Diamond's best-selling book *Collapse* (2005). He points to their leaky boats, the treeless, wind-swept landscape, rock-mulched gardens, and modern signs of erosion in one portion of the island as evidence of their misery. Based on this sorry scene, he concludes that Rapanui society ultimately failed to navigate the essential challenges of their environment, echoing the thesis of his book. Diamond has come in for much criticism for his characterizations of the Rapanui and Maya, in particular, in his effort to make the worthy point that humans would be wise to heed the fragility of our environment. But the more relevant story of the Rapanui may be one of adaptation and resilience in the face of a difficult environment in one of the most isolated places on the planet, a case made by biologist Jan Boersema (2015). By the time Roggeveen set foot on the island, the Rapanui had survived and changed their culture in several important ways over the more than 500 years since their arrival. In those years they adapted to the deforestation of their island and managed the transition from an expanding population to one confronting the limits of its environment, while at the same time managing to create the nearly 1000 stone moai statues that captivated visitors from Roggeveen to this day. Evidence of land use suggests that despite claims of a population crash or collapse, while some areas of the island were becoming less heavily used and occupied, other more favorable areas were still growing at the point of Roggeveen's visit (Stevenson et al. 2015).

The tremendous interest in the history of Rapa Nui and the effort devoted to understanding it has led to some remarkable discoveries. However, the size and nature of the population that lived there in the time before European contact remains a heated topic. In the following we will consider two models of population size parameterized for Rapa Nui, each proposed as an improvement on the carrying capacity approach.

The first was developed by Bayliss-Smith (1980) to incorporate the idea of human welfare into the carrying capacity debate. Why would islands in Fiji in the 1970s be observing depopulation if by any measure they were below their carrying capacity? He thought the answer lay at least in part in human agency, or people acting on their desires and expectations about what life should be like. In practical terms, what happens if we assume people are only willing to work at some fraction of the theoretical maximum? As Ester Boserup (1965) described in her groundbreaking work on population pressure, it is often possible to get more

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their childhood, compared to other ancient samples from the Pacific and to Medieval European samples."

food energy per unit of land, but in preindustrial societies without pack animals, the price of this intensification is paid in human energy. Which brings us to a key question: Why would anyone choose to work harder than they already do? There are, of course, reasonable answers, including that you foresee or feel the consequences of population growth and want more food, or perhaps you are compelled to in order to satisfy the need for tribute, taxation, or exchange for other things you require or desire. But several years after his efforts to model atoll populations (Bayliss-Smith 1974), Bayliss-Smith became interested in what happens if people limit their work effort. How do variable levels of labor input affect population? And how do we account for surplus production? Certainly, an agrarian population that is required to feed a large non-producing class has to work harder to maintain the same standard of living as one that does not.

Bayliss-Smith (1980) developed a 10-step process to incorporate work effort and level of surplus production into the study of population (Box 20.1). The first five steps are required to calculate the carrying capacity, by which he means the population that can be supported at the "ultimate level of intensity that is acceptable" (Bayliss-Smith 1980) from a staple production system contributing some known fraction of the total diet. The two models we discuss in this chapter conform to the Hunter-Anderson and Zan (1985) "intensification hypothesis," in which we are mostly concerned with the production of starchy staples as the most important and limiting elements of the islanders' diet. The assumption that protein was not limiting is supported by DiNapoli et al. (2019), who surveyed the literature for information on the island's resources and described a significant input of marine foods.

The final output contains what Bayliss-Smith called "standard populations," which are population sizes that correspond to a certain expectation of labor and a certain fraction of surplus production in a given place using specified crops with a specified technology. That is extremely powerful. And if we know something about the surplus requirements and/or the expectation of labor, it allows us to narrow the likely population size estimates. Bayliss-Smith (1978) found that on many small islands of the Pacific the effort by the productive population was typically in the range of 10–20 person-hours per week.

Box 20.1 Calculating Bayliss-Smith's Standard Populations

Bayliss-Smith (1980) describes a 10-step process for calculating "standard populations," which are the population sizes that account for the effects on carrying capacity of differing levels of work intensity and also for various levels of surplus production. The original work includes description and several worked examples. The first five steps calculate the carrying capacity, which assumes maximum intensification of agriculture and that all food goes to support an egalitarian population. The next five steps account for how total yields respond to diminished intensification (labor inputs) and how

(continued)

Box 20.1 (continued)

the diversion of increasing fractions of production into "surplus" affects population size. The final step assembles the data into a table of population sizes under combinations of labor intensification (hours) and surplus.

Step 1 specifies the quality and extent of land available to the population. **Step 2** describes the economy, specifically the fraction of total calories derived from the staple production and the fraction of the population that is actively involved in production. **Step 3** describes the "maximum acceptable intensity level," which refers to the minimum return to labor. Specifically, if a person-hour of labor provides less than 1750 kcal, then it is unlikely to be deemed worth planting. **Step 4** requires the calculation of productivity of land and labor. These vary according to the crop and context. Bayliss-Smith (1980) assumes in his worked examples that a person-hour of work expends 175 kcal. This figure is used to turn the agricultural labor requirement (the observed or estimated person-hours required to produce a hectare of a particular crop) into human energy input requirements. We must also estimate the food energy output per hectare in the particular context. **Step 5** calculates the carrying capacity from these figures:

$$K = \frac{YA\left(^{1}/_{F}\right)}{R},$$

where Y is the crop yield in kcal/ha/year, A is the area in ha that meets the minimum return to labor threshold, F is the fraction of the energy in the diet that comes from the modeled staples, and R is annual energy requirement on a per-person basis, in kcal/year. The first two factors in the numerator determine the total staple output, staple fraction is the fraction of the diet that comes from these agricultural staples, and R is the energy requirement per individual per year, which Bayliss-Smith estimates at 800,000 kcal/year, or 2192 kcal/day.

The remaining steps address the questions of welfare. **Step 6** calculates the person-hours each worker is required to labor to produce the maximum food output. For this, we need to know something about population structure and the division of labor. If only men work in the fields and men make up half the population and only half of these are working age, then the "productive population" is 25% of the total. These workers are responsible for all the person-hours required to produce the staple, so we calculate person-hours per week required of the typical worker. In **Step 7,** you begin to assemble a table, starting with the population size at various fractions of K (i.e., 90% K, 80% K, etc.), and determine the size of the productive population for each. Then you calculate the food energy required to feed each population and the number of person-hours per week required of the productive population in each case. In

(continued)

Box 20.1 (continued)

his worked example, a reduction in population size from K to 90% of K meant that the productive population's effort fell from 28.1 to 17 hours per week.

Step 8 is the creation of a graph of output per person-hour vs. output per hectare of all land in the agricultural system, including fallowed land. **Step 9** involves the calculation of person-hours per worker when the population is required to produce a surplus, expressed as a fraction of the subsistence requirement (S). That is, if the population produces $S + 50\%$, each worker now has to work some additional amount to provide the extra. Some combinations of population size and surplus may not be feasible, as the food energy required exceeds the potential output of the available land, or the effort required to maintain a population exceeds what most subsistence populations regard as acceptable. **Step 10** assembles a table of results with producer population person-hours on the rows and total production (subsistence plus surplus) across the columns. The entries are population sizes. This step requires interpolation from the data in the table created in Step 7.

The parameterization of Bayliss-Smith's model for Rapa Nui involves making assumptions, some of them "heroic," to borrow a phrase from population biologist Shripad Tuljapurkar (Pers. Comm.). Some of these unknowns have already been estimated by Bayliss-Smith and we use these values where better, more local, options are unavailable.

For Step 1, the island of Rapa Nui is approximately 164 km^2 in area, and 3134 ha, or 19%, was deemed suitable for agriculture using shifting cultivation (Puleston et al. 2017). However, in low-yield scenarios some or all of this land may be considered too poor to farm, which is discussed below. Step 2: Following Bayliss-Smith (1980), we assume that sweet potato was the dominant starchy staple in the diet and that it provided 80% of the energy in the diet, the remainder coming from all other sources, including domesticated animals, fishing, and garden foods. The model only tracks labor dedicated to farming the main staple(s), and the acquisition of all other foods and the completion of all other tasks are assumed to be done in the remainder. This parameterization is not tied to any particular era in Rapa Nui history, although we assume that all the agricultural land was in regular rotation (i.e., had been cleared of primary forest) and that the island had completed the early phase of human habitation when some native resources (e.g., wild birds) were more plentiful. For Step 3 we accept Bayliss-Smith's minimum threshold for return on labor in subsistence economies as 1750 kcal/person-hour. Step 4 requires the description of the relationship between human energy input and energy output (crop yield). Bayliss-Smith (1980) includes an estimate for sweet potato in the New Guinea Highlands in his Figure 5, but laments the paucity of data. Puleston et al. (2017) used a nutrient cycling model of sweet potato growth parameterized with climate data gathered on Rapa Nui. That model bracketed likely nitrogen availability, which is unknown, including a low-N and high-N scenario. It is unsurprising that yields per hectare would be lower than observed in more tropical parts of the Pacific and those with more plant-available nitrogen. Much of the data on sweet potato cultivation comes from Papua New Guinea, but as the yields reported there are so much higher, and the labor estimates are so much lower there than elsewhere in Polynesia, it suggests that they are not representative of conditions in Remote Oceania. Unfortunately, there are only a handful of estimates of labor inputs for traditional sweet potato farming from outside New Guinea. We averaged the four estimates known to us, two from Burtenshaw and Harris (2007) and one each from Christiansen (1975) and Jones (1989) to get 2810 person-hours/ha (CV $= 0.71$, where CV is the coefficient of variation, or standard deviation divided by mean).

For Step 5 for our two nitrogen scenarios we calculate K, the carrying capacity for Rapa Nui, following Bayliss-Smith's (1980) assumption that each person requires at most 800,000 kcal per year, and at the yields representing maximum labor intensity, or continuous cultivation. Replacing Y in the carrying capacity equation above with the low-N continuous cultivation value of 1.59x10^6 kcal/ha/year and the high-N equivalent of 5.56 x10^6 kcal/ha/year gives $K_{lo} = 7786$ and $K_{hi} = 27{,}227$ individuals, respectively.

For Step 6 we follow Bayliss-Smith's assumption that only men work in the fields and men represent half the population. Further, only half of the men are of working age, meaning that all field labor is the responsibility of 25% of the whole population. The "productive population" (worker pool) at K_{lo} and K_{hi} is thus 1947 and 6807, respectively. The 8,806,540 person-hours per year required to tend the entire island's crops results in a work week of 87.0 and 24.9 hours per week in the low-N and high-N scenarios, respectively, for the productive population. Already we can see a problem. It is not impossible for preindustrial workers to put in the hours of a junior partner at a white-shoe law firm, but recall that based on Bayliss-Smith (1978) 10–20 hours per week is more to be expected. But these are the hours required to maintain K, the theoretical maximum population size, and there are tradeoffs to consider. Bayliss-Smith (1980) examines the dependence of population size on the expectation of labor (hours worked per week) and the size of the burden of surplus, meaning any food that exceeds what is required for the population's upkeep at the level specified.

Following Bayliss-Smith (1980) we calculated the work hours required from the productive population at 10 population sizes from 25% K to K, and under seven surplus regimes from no surplus to the subsistence requirement (S) plus 150%. For each nitrogen scenario in Puleston et al. (2017) we had three yield values, each associated with a level of intensification (fallow regime). Following Bayliss-Smith (1980), we fit piecewise linear functions to the returns to labor vs. returns to land for each nitrogen scenario to find yields for the levels of labor inputs required to fill out our tables. Finally, we used a spline interpolant in MATLAB to determine intermediate values and present the results in a form where population size is the dependent variable, varying with weekly labor expectation and surplus requirement. The resulting "standard populations" are found in Tables 20.1 and 20.2. Figures 20.1 and 20.2 illustrate the dependence of maximum population size

Table 20.1 Standard populations for the low-N scenario on Rapa Nui, following Bayliss-Smith (1980). The values in the table are the population sizes predicted under the combination of expectation of labor and surplus production. *S* represents subsistence production, and the level of surplus required of the population is proportional to this value. Missing values in the upper left represent combinations falling below the minimum return to labor. Missing values in the lower right represent places where the population size fell below 25% *K*

Low-N regime							
Weekly Hrs	Standard populations at stated productive levels						
Per worker	S	S + 10%	S + 20%	S + 30%	S + 50%	S + 100%	S + 150%
50							
40						2344	
30			4375	3880	3120		
25	5228	4553	3997	3506	2759		
20	4686	4022	3444	2981	2221		
15	3782	3114	2564	2078			
12.5	3079	2406					
10	1997						
7.5							

Table 20.2 Standard populations for the high-N scenario on Rapa Nui, following Bayliss-Smith (1980). The values in the table are the population sizes predicted under the combination of expectation of labor and surplus production. *S* represents subsistence production, and the level of surplus required of the population is proportional to this value. Missing values in the upper left represent unviable combinations, either exceeding *K* or falling below the minimum return to labor. In the lower right, they represent combinations where the population size fell below 25% *K*

High-N regime							
Weekly Hrs	Standard populations at stated productive levels						
Per worker	S	S + 10%	S + 20%	S + 30%	S + 50%	S + 100%	S + 150%
50						13,653	9833
40					18,573	11,873	8875
30		25,566	22,826	20,457	16,467	10,638	7839
25		23,842	20,909	18,479	15,060	10,146	7292
20	24,716	21,312	18,641	16,162	13,640	9382	
15	21,026	18,556	16,762	14,934	12,274	8031	
12.5	19,951	17,522	15,743	14,069	11,321	7036	
10	18,599	16,208	14,271	12,547	9937		
7.5	16,070	13,761	11,755	10,083	7394		

on the expectation of labor and the burden of surplus production under low and high nitrogen availability, respectively. The three-dimensional surface is similar in both cases, although the scale differs. Unsurprisingly, population is maximized when labor is plentiful and the surplus requirement is small. However, increasing labor inputs eventually results in nonviable populations because the investment in additional labor is not rewarded with enough additional production to justify the expense. The return to labor falls below the subsistence threshold of 1750 kcal per

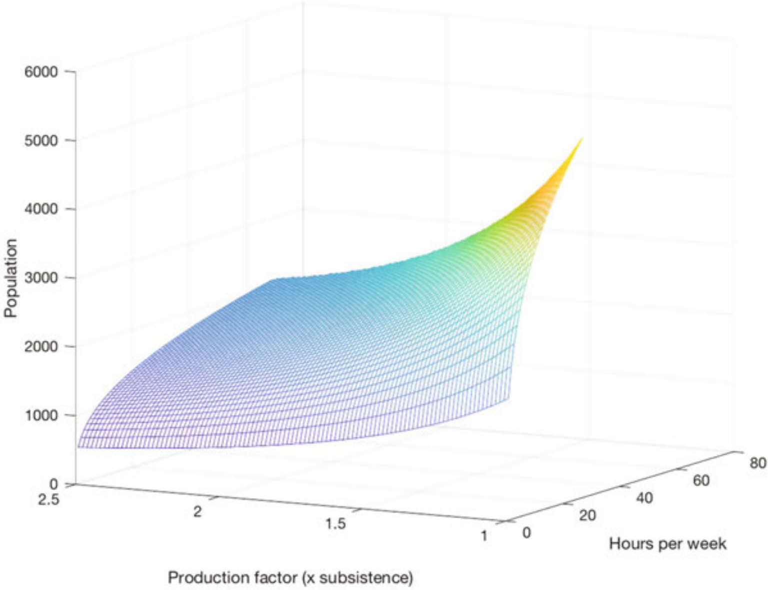

Fig. 20.1 The surface of Rapa Nui standard populations as production requirements and hours worked per week vary in the low-N environment under the Bayliss-Smith (1980) model, parameterized as discussed in the text. The maximum population of 5291 occurs when there are no requirements to produce a surplus and when the productive population works 28.0 hours per week. Increasing intensification beyond this point results in a return to labor below the subsistence threshold. The axes are oriented to give a sense of the shape of the surface, which might make it difficult to accurately identify population levels

hour of work, making the combination untenable. Also, the surfaces show that as hours per week increase, the response flattens out, meaning a diminishing return for each unit of extra labor. Population size is most responsive to the burden of surplus when the demands are small. At higher levels of surplus, the response is quite linear.

Unfortunately, the uncertainty surrounding nitrogen availability leaves us with the conclusion that the maximum precontact population on Rapa Nui was probably somewhere between the low estimates and the high ones. However, this approach does narrow the range of solutions, namely by allowing us to exclude some combinations of parameters because they rely on yields that would likely never be realized as the return to labor is too low. Imagine a poor hectare that could grow a meager pile of sweet potato, but it required all the same labor to prepare, plant, and tend as a better patch. At some point, even if you were starving, it might not be worth it to grow there because the food it produced would not compensate you for the energy you put in, or that other activities might give you a better return on your efforts.

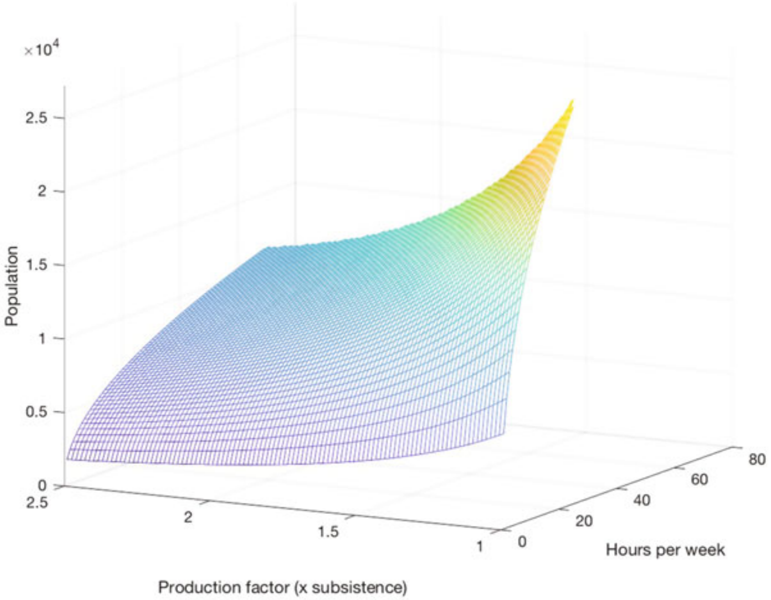

Fig. 20.2 The surface of Rapa Nui standard populations as production requirements and hours worked per week vary in the high-N environment under the Bayliss-Smith (1980) model, parameterized as discussed in the text. The maximum population of 27,227 occurs when there are no requirements to produce a surplus and when the productive population works 24.9 hours per week. The surface is quite similar to the low-N equivalent, although the scale of population is greater

5 Modeling the Effects of Hunger on Rapa Nui Population

After estimating sweet potato yield in the two Rapa Nui nitrogen scenarios, Puleston et al. (2017) used those values to consider population size in the space-limited model described by Puleston and Tuljapurkar (2008) to capture the dynamics of a subsistence agrarian population that grows in size until it eventually finds it is running out of land to farm. In contrast to the approach of Bayliss-Smith, this model (illustrated in Fig. 20.3) is built around the concept of the food ratio, which is the ratio of food availability to the amount required to maximize survival and fertility (Lee and Tuljapurkar 2008). If the food ratio is 1 or greater, then the population is capable of producing as much food as it needs to avoid hunger, and vital demographic rates are assumed to be maximized. If the food ratio falls below 1, then survival and fertility rates begin to decline. If a small population arrives in a suitable location for agriculture and the initial food ratio exceeds 1, the population will grow at its maximum (baseline) rate. This small population might only have enough labor available to farm a small part of the land available. It continues to grow at its baseline rate while expanding the area of cultivation and perhaps

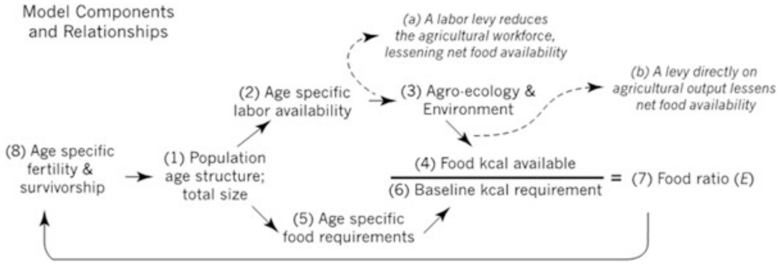

Fig. 20.3 A schematic of the space-limited model. Given some population of a given size and age structure we can calculate food availability based on its labor potential and the characteristics of the food production system. The minimum number of calories required to avoid any negative effects of hunger can also be calculated. The ratio of availability to need (the "food ratio") is used to determine the age-specific fertility and mortality rates that generate the population at the start of the next cycle. A small colonizing population on suitable land in a constant environment will grow at its maximum rate until the food ratio falls below 1. At this point hunger begins to reduce fertility and survival rates and growth slows at it approaches an equilibrium. The dotted lines indicate where tribute and taxation influence the system, whether taken as a work levy (a) or as a food levy (b). Figure adapted from Winterhalder and Puleston (2018)

intensifying production, with diminishing returns as it approaches the maximum of total production, which occurs when all land is in use. Along this trajectory eventually the food ratio falls below 1 (the number of mouths grows, but land is limited) and the effects of hunger begin to rein in growth. The population approaches an equilibrium where the increasing death rate and decreasing birth rate balance and growth slows to zero.

Puleston et al. (2017) determined the equilibrium population size for Rapa Nui for a variety of scenarios, chosen to represent likely combinations of environmental and cultural parameters that remained unknown (also see Lipo et al. 2018 and Puleston et al. 2018) (Table 20.3). Expected sweet potato yield was modeled across three intensification levels (continuous cultivation, 5 years of cultivation followed by 5 years of fallow, and 3 years of cultivation followed by 15 years of fallow) and across the two nitrogen availability regimes. The authors also considered three cultural features: the requirement to pay tribute to maintain a non-producing elite, the fraction of the working-age population working in agriculture, and the presence of rapid and strong fertility control measures in response to increasing hunger. The tribute in the hierarchical scenario was assumed to be fixed at 10% of total food production. The worker fraction was set at 50%, 75%, or 100% of the working-age population. The authors assumed each full-time equivalent worker (working-age population times worker fraction) could farm just under a single hectare as an ongoing responsibility, representing a conversion of the expectation of labor into units of land. However, as more and more of the total agricultural area was put into use, the return to labor decreases, leading to an asymptotic (ever-slowing) approach to full utilization of land. This feature of the space-limited approach captures the expected decreases in quality of remaining land as better areas are allocated first,

Table 20.3 Equilibrium population sizes on Rapa Nui (commoners and elites) under the space-limited model under multiple scenarios. Empty cells represent nonviable combinations under the assumptions of the model. After Puleston et al. (2017) Table 2

Organization	Egalitarian						Hierarchical					
Pop Control	No Fertility Control			Fertility Control			No Fertility Control			Fertility Control		
Work frac	0.5	0.75	1	0.5	0.75	1	0.5	0.75	1	0.5	0.75	1
Low-N fixation regime												
Continuous		4023	6176			1952			2633			
Shift 5/5	3889	5775	6385	42	2655	3613	11	3612	4933		138	1951
Shift 15/3	5165	5319	5343	3103	3437	3519	4241	4703	4816	2070	2835	3075
High-N fixation regime												
Continuous	27,752	28,912	29,120	16,155	18,482	19,094	22,069	25,285	26,132	9703	14,786	16,443
Shift 5/5	22,717	22,866	22,878	14,601	15,094	15,175	19,977	20,661	20,774	11,862	13,298	13,660
Shift 15/3	16,778	16,778	16,778	11,135	11,141	11,142	15,243	15,252	15,253	10,059	10,123	10,128

and the decreasing efficiency of infill plots and plots at greater distances from home. Adding another worker to a crowded field system does less to improve the total yield than it might have when there was much unused land left.

In the absence of fertility control, Puleston et al. (2017) used the response of fertility and survival rates observed in famines (described in Lee and Tuljapurkar 2008), and in the fertility control scenario the authors dramatically increased the responsiveness of fertility to hunger to examine the consequences of strong attempts to limit population size when it was detrimental to welfare. In this scenario, when the food ratio drops below 1 fertility quickly declines and the population approaches equilibrium at a smaller size but with greater food availability per capita (Puleston et al. 2014). In practice fertility control could take multiple forms, including infanticide, delayed onset of marriage, or coitus interruptus, all of which have been described in traditional Polynesian societies. It is also probable that at times survival rates were diminished either intentionally or not (high-risk voyages of exploration, armed conflict, human sacrifice) to similar effect on the equilibrium population size. If the increases in mortality decrease the most reproductively successful age classes, fertility will also decline.

Other key assumptions in the application of the space-limited model to Rapa Nui were that 25% of the labor pool of the population was diverted from agriculture in the form of tribute, equivalent to a tax paid in the form of labor in addition to the tribute paid in the form of food. Also, the elite (and non-agricultural) population was modeled as a simple 1% of the size of the commoner population.

The study confirmed that soil nitrogen availability has a powerful effect on yields, which has a subsequent effect on population size. Of the social factors, fertility control generally had the largest effect on population size while at the same time keeping the equilibrium quality of life high. Under strong fertility control the population was well fed, and life spans of those surviving infancy were near their maximum. The effect of social stratification was not great, but the model was set to exact relatively modest tribute in food and labor. Generally, population sizes decrease as fallow requirements increase, but there are exceptions where labor is in short supply. This occurs most often under combinations of continuous cultivation (maximum area) at lower worker fractions (fewer workers) in the low-N scenario (low returns to labor).

6 Comparing the Two Models

The space-limited model shares some features with Bayliss-Smith’s (1980) model in that population size is conditional on measures of welfare or well-being. Where Bayliss-Smith (1980) highlights the effect of the expectation of labor inputs (hours worked per week), the space-limited model is centered on hunger and its effects on the growth rate. Bayliss-Smith includes the expectation of food availability as a parameter to calculate population size, and the space-limited model parameterizes an expectation of labor in terms of how much land a typical worker can farm. Both models also include an estimate of the fraction of the population directly involved in agriculture.

Bayliss-Smith's calculation of *K*, or the maximum number of people who might be fed under the most efficient use of resources available, is comparable to the space-limited model's equilibrium population under the default assumptions: egalitarian organization, no fertility control, and continuous cultivation. The worker fraction has typically been assumed to be 50% of the working-age population in previous applications of the space-limited model, and this matches Bayliss-Smith's (1980) parameterization. That the Bayliss-Smith model's maximum of 27,227 people (at 24.9 hours per worker per week) in the high-N scenario is comparable to the 27,752 people in the space-limited model should not be particularly surprising given that they both rely on the same estimates of total food production. But there are differences. Note that the space-limited model is responsive to additional inputs of labor, resulting in a maximum population of 29,120 when the entire commoner working-age population participates in agriculture. Also, under the Bayliss-Smith assumptions, the entire population receives the equivalent of 2192 kcal/day, while in the dynamic space-limited model the population initially is able to receive the desired 2785 kcal/day, but at equilibrium the allotment has fallen to 1917 kcal/day.

In the low-N scenario Bayliss-Smith's model predicts a maximum population of 5291 (at 28.1 weekly hours per worker), which is less than *K* because it assumes workers will reject any situation that returns less than 1750 kcal/ha. In the space-limited model, the low-N scenario is an extremely difficult balancing act. The losses of N from the system under continuous cultivation make it inefficient, and populations are small or nonviable. We expect a population under those limitations to employ some degree of fallow to increase total productivity. The alternating 5-year fallow regime yields an equilibrium population of 3889, and the 15-year fallow with 3 years of cultivation regime supports 5165 people in the egalitarian, no fertility control scenario with 50% of the working-age population employed in agriculture. These maximum populations would be reduced as demands for surplus or tribute increased, or if the population refused to work the hours the calculations require, or if there were any degree of fertility control.

While the degree of nitrogen availability remains a vexing unknown, we can narrow the range of several other parameters to eliminate less likely population numbers. One such change is to assume that most subsistence economies rely on 10–20 hours of agricultural labor per week (Bayliss-Smith 1978) and expand that to 30 hours per week to include some outliers, simplifying the picture. We can also treat the demand for surplus in the context of what is known about Polynesian social stratification specifically. The vast majority of Polynesian populations had some degree of social inequalities, although the extent was varied. On larger and more productive islands of the Pacific (e.g., the Hawaiian Archipelago, per Hommon (2009)), there was a larger proportion of non-agricultural elites and a more complex bureaucracy than on smaller volcanic islands and atolls, where the difference in the lifestyles of elites and commoners could be minor. Hommon (2014) estimates a chiefly class that was 2.3% the size of the commoner population in the leeward Kohala field system of Hawai‘i, and that approximately 3% of the commoner population would have been required as full-time herders of the pigs required for their needs. Elsewhere Hommon estimates the chiefly class on Hawai‘i Island was 1–2% of the population (Hommon 2020), but it required 3–6% of the total agricultural land to feed the pigs they required in tribute (Hommon 2008). He calculates the cost of feeding a male member of the chiefly class was 9 to 17 times greater than that of a commoner.

If we use Hommon's sketches of the Hawaiian elite as a basis, while acknowledging that Hawai‘i probably had greater social inequalities than Rapa Nui, Puleston et al.'s (2017) estimate of elites as 1% of the commoner population size seems a conservative but reasonable assumption. The distinction between the commoner and elite subpopulations lies in agricultural labor contributions and the differences in diet. The cost of maintaining the elite class might be in the neighborhood of 10 times (in terms of calories) the cost of maintaining an equivalent number of commoners, after we account for the fact that the elites included women and children and Hommon's estimates focus on male consumption of pig meat. Consider also that feed conversion efficiency for chickens (the only domesticated meat source for the Rapanui) is about twice that for pigs, meaning that pigs take much more food energy inputs than poultry for the same caloric output in meat. In terms of surplus to subsistence production as Bayliss-Smith (1980) defines it, this is equivalent to N_C times (elite fraction) times (per capita kcal) times (elite need multiplier), where N_C is the commoner population size, elite fraction is the elite population as a fraction of commoner population (0.01), per capita kcal is commoner food need (2192 kcal/person/day), and elite need multiplier is the multiplier to convert commoner food need to elite food need (10), yielding a result expressed in kcal per unit time. To express surplus production as a percentage of subsistence production we divide this by subsistence production (N_C x per capita kcal) and multiply by 100. The resulting surplus is 10%. If these parameters are accurate, then we can narrow the standard populations from Tables 20.1 and 20.2 to the column "S + 10%" and the rows in the vicinity of 20 hours per week or less. Let us assume that 30 hours per week dedicated to sweet potato production is a reasonable maximum. That corresponds to a maximum commoner population of 4913 and 25,566 in the low-N and high-N regime, respectively. Including elite populations would add 1% to these totals, yielding 4962 and 25,822, respectively.

For comparison, we can update the population projections in the Puleston et al. (2017) parameterization of the space-limited model to incorporate a number of Bayliss-Smith's assumptions. Specifically, we will for this parameterization assume that sweet potato production represents 80% of all calories, rather than 100%. The 10% tribute in food and the elite population modeled as 1% of the commoner population remain unchanged. We impose fertility control, tuned to achieve an equilibrium food availability of 2192 kcal/person/day to match Bayliss-Smith's (1980) parameter. The expectation of labor remains unchanged. We eliminate the requirement that 25% of labor be provided in tribute. We also incorporate Bayliss-Smith's lower limit on returns to labor (1750 kcal/ha), which eliminates any agricultural zone that yields less than 4.51 mt/ha/year of sweet potato. This minimum productivity threshold eliminates all agricultural area in the two more intensive cultivation regimes in the low-N scenario, but does not affect the low-N long-fallow regime, or any of the three high-N cultivation regimes.

The results of the space-limited model after reparameterizing to incorporate Bayliss-Smith's (1980) parameter values do not change the range of the low-N scenario very much from the results of Puleston et al. (2017). The more intensive usage (no-fallow and short-fallow) scenarios are nonviable, and only a 15-year fallow, followed by 3 years of cropping, allows for a sustainable population. However, the high-N scenario generates generally larger populations than the previous parameterization. The greatest contributors to the increases are the assumption that only 80% of the population's food comes from sweet potato, and that under fertility control the population equilibrates to Bayliss-Smith's (1980) caloric intake of 2192 kcal/worker/day, as opposed to the 2785 kcal/worker/day under the more extreme fertility response in Puleston et al. (2017). In addition, we have eliminated a requirement in this iteration that 25% of available labor be diverted from agriculture to meet other societal obligations. The most appropriate comparison to Bayliss-Smith's standard populations is the continuous cultivation scenario, as the standard population approach assumes the most intensive land use available to calculate maximum population size. The high-N continuous cultivation space-limited population estimate of 26,393 compares well with the 25,566 Bayliss-Smith standard population in the high-N scenario at S + 10% and 30 hours of work per week. Note also that the standard population calculations do not include the elite population, which could add another 256 individuals.

As closely as these models agree, it remains impossible with the information we have to distinguish between two quite different pictures of life on Rapa Nui at its peak of population. In the absence of the use of nitrogen-boosting sugar cane that was used elsewhere in Polynesia to border dryland plots (Kamakau 1976, Lincoln and Vitousek 2016, Marshall et al. 2017) and is believed to have predated European contact on Rapa Nui, the island was probably quite sparsely inhabited. The population would have been small and worked relatively long hours tending plots that could only be used maybe one year in six to allow the buildup of nutrients required to make it worth the effort. However, if a windbreak of sugar cane is allowed to decompose as mulch the expected yields increase from an untenable average of 1.46 mt/ha/year of sweet potato to as much as 5.09 mt/ha/year under continuous cultivation. Such a difference is remarkable with regard to the prospects for the size and welfare of the human population and reinforces the high dependence of Rapanui society on soil resources and agricultural innovation.

7 Living in a Variable World

Environmental variability and its effect on population size and well-being can be key in various island settings. Even in well-controlled experiments of traditional agriculture, yields can vary wildly from year to year. Burtenshaw and Harris (2007) planted two experimental gardens with kumara sweet potato in Aotearoa New

Zealand using traditional techniques and observed a coefficient of variation in yield of 0.43 over seven years at one location and 0.47 over six years at another. These would be considered highly variable yields in any agricultural system (where CVs of 0.2 or 0.3 are more commonly assumed), but in a place like Rapa Nui, with limited ability to store food from one year to the next, the population-level consequences would likely be much more extreme. Winterhalder et al. (2015) found that "variance compensation" in a preindustrial subsistence agrarian context required farmers to over-plant in an average year to avoid the harsh consequences of coming up short. In other words, to prepare only for the average shortfall is bad policy given the consequences of rare but really poor yields. In the Rapa Nui context, we do not have the same system of individual farmers making decisions about seed and effort allocations, but the underlying problem is the same. If your food comes from a crop with a high degree of variability you can either ride the wave in which some years see high survival and fertility rates and every once in a while suffer calamitous famines, or you can limit your population to a size that can still find enough food even in bad years.

The dynamics of taxed natural fertility populations in a variable environment were discussed in Winterhalder and Puleston (2018). Analyzing a version of the space-limited model, they found that, first, if two natural fertility agrarian populations achieve identical average yields, but one is variable and the other constant, the population with the variable food supply will on average be expected to be significantly smaller. Figure 20.4 shows the commoner population on our simulated Rapa Nui landscape under the space-limited model parameterized for comparison to Bayliss-Smith (1980). This represents the low-N scenario under the shifting 15/3 cultivation regime from Table 20.4. Instead of the constant yield we have considered to this point, each year we draw a yield value from a normal distribution with the identical mean in all simulations. Each draw is independent of previous draws. How much the yield varies from year to year is determined by the coefficient of variation. The constant-yield scenario stabilizes after about 450 years at 4883 people (ignoring the 1% elite population here, whose inclusion totals the 4932 found in Table 20.4). As variation in yield increases, the population size also becomes more variable and, importantly, smaller. At yield CV = 0.2, the long-run population is 8.2% smaller than the default, constant-yield case. At yield CV = 0.3 it is 17.5% smaller, and at yield CV = 0.4 it is 31.2% smaller than the constant-yield population.

A second implication from Winterhalder and Puleston (2018), of particular importance to small, isolated populations, is that the form of taxation and its magnitude contribute to the risk of local extinction. The risk becomes particularly acute when the elite insist on a fixed level of total tax revenue (in the form of food) in a variable environment. See their Figure 8 for an illustration of the half-lives of various populations under combinations of a fixed tax and yield variability. Their Figure 6 describes the state space of a population under a per capita tax in food. There exists a trade-off between commoner population size and the size of the per capita food levy. The elite class may attempt to maximize total taxes by incrementally increasing the per capita rate, but with each step they come closer and

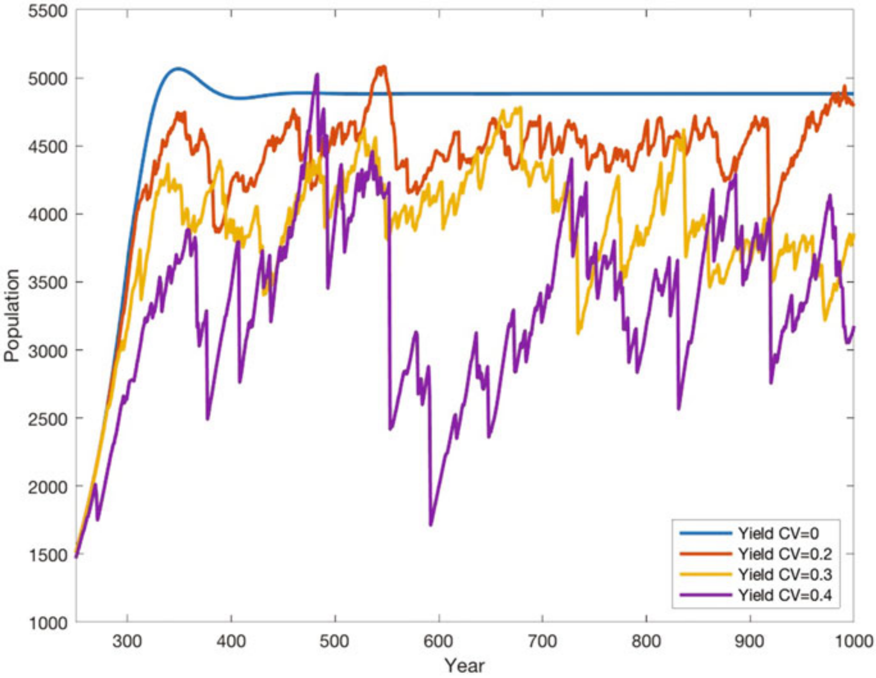

Fig. 20.4 Simulated Rapa Nui commoner population trajectories under variable yields, starting at year 0 with 20 individuals (detail). The average yield should be identical in all scenarios. The blue line represents the constant-yield scenario in low-N long-fallow conditions under the space-limited model parameterized for the Bayliss-Smith (1980) comparison (see Table 20.4 low-N, shifting 15/3 scenario). The mean between year 450 and 1600 (after the populations have settled into their long-run dynamics) is 4883 commoners (in the case where CV = 0). The reddish line is a CV = 0.2 scenario with the same mean yield and other parameters. Its long-run average is 4840 (CV = 0.04). The yellow line is yield CV = 0.3 and the population averages 4030 (CV = 0.08), and the purple line is yield CV = 0.4, where the average population becomes 3358 (CV = 0.18)

closer to the point of unsustainability in which the burden is too great to bear without inducing starvation and negative population growth. We can imagine this balancing act being attempted and even accomplished in a constant-yield environment, but in the case of variable yields it becomes an extremely dangerous endeavor. A year of bad yields with a high tax burden might trigger a mass mortality event that would require nimble management to recover from. There are, of course, checks that might bolster the stability of the system. Hommon (2020) discusses the process of tax collection on Hawai‘i, in which communities that were seen as falling short of their obligations were punished and plundered. At the same time, chiefs who were seen as extortionate could be murdered as a response. But usually taxes were based on a subjective assessment of the wealth of the community: its size, the size of its working population, and history of tax payments. “To reduce the risk of repression from above or rebellion from below, various participants including

Table 20.4 Sustainable Rapa Nui population sizes under the space-limited model using Bayliss-Smith's (1980) assumptions, where applicable, and Puleston et al.'s (2017) assumptions elsewhere. In the low-N regime only the lowest-intensity land use meets the minimum return to labor of 1750 kcal/ha. We assume that 50% of the working-age population is engaged in agriculture and a moderate degree of fertility control is practiced. The elite population demands an additional 10% of subsistence production and is 1% the size of the commoner population

Low-N fixation regime	
Continuous	–
Shift 5/5	–
Shift 15/3	4932
High-N fixation regime	
Continuous	26,393
Shift 5/5	21,764
Shift 15/3	16,095

ahupua‘a [the basic unit of Hawaiian political division] residents, *ahupua‘a* chiefs, tax collectors, and the king, may have applied such information to arrive at estimates of an *ahupua‘a*'s tax liability that could be negotiated with the other parties" (Hommon 2020). The incentive for chiefs to be flexible in their demands (within limits) was strong, as this would help populations to ride out "bad" years while still maintaining social inequalities. Other forms of buffering the effects of lean years would include the suppression of population numbers via the diversion of labor away from subsistence activities into costly public projects. Graves et al. (1995) and Hunt and Lipo (2011) proposed the diversion of labor required to build and move Rapa Nui's many moai statues, as well as other costly investments of resources into efforts that provided no immediate benefit to survival or fertility was an adaptive trait that limited population size with the benefit of minimizing the risk of famine.

Manifestations of social inequalities and the accompanying demands for tribute may have complex consequences for the dynamics of an agricultural population in the face of variable yields. It is likely that these consequences increase the burdens on the commoner population in ways that reduce its average size compared to static calculations based on estimates of carrying capacity, perhaps as much as 30% or more (Fig. 20.4, yield CV $= 0.4$) even after accounting for numerous other likely factors.

8 Independent Estimates of Rapa Nui Population

The Bayliss-Smith quote that opens this chapter reminds us of the limitations of models. Models can be useful, but are limited by the questions they are crafted to address. The two models we have considered are concerned with a theoretical question: How many people *could* have lived on Rapa Nui? This is a separate but related question from: How many people *did* live on Rapa Nui? In this section, we consider the best estimates of Rapa Nui's population near the time of contact, along with more general estimates of Polynesian population density, and briefly compare them to the model estimates of maximum population under our assumptions.

In his careful survey of the records of early European visitors, Boersema (2015: Table 6.1) summarizes the observations on population size and ventures a guess that in the eighteenth century the island's population stood between 1500 and 3000 individuals. While Roggeveen and his shipmates made no estimate of population (other than to remark on "thousands" of swimmers), we know that life on Rapa Nui was changing dramatically in between 1722 and the multiple contacts between 1770 and 1804. It may be impossible to rule out a decline in population immediately after Roggeveen's visit similar to the declines that occurred elsewhere in Polynesia after European contact. Hunt and Lipo (2011) consider this possibility. Estimates and best guesses at to the island's maximum precontact population among the modern experts vary. At the low end are Hunt and Lipo (2011:32), who suggest a maximum population of about 3000, probably achieved within 200 years of arrival, around 1350 AD. Jo Anne Van Tilburg (1994) considered the estimates of several previous researchers based on archaeological features and concluded that 7000–9000 seemed a reasonable number. At the high end, Jared Diamond (2005) settled on 15,000 after some calculations and consultation with other researchers.

The population densities of comparable populations elsewhere in Polynesia may be useful here. Kirch (2007c) estimated from archaeological data the densities in the more productive zones of Kahikinui, Maui at between 43 and 57 persons/km^2, and 19–25 persons/km^2 over an entire territory (*ahupua'a*): "These values are on the low end of ethnographically documented population densities in Polynesia and are probably realistic in view of the environmental marginality of Kahikinui" (ibid.:101). He assumed 4.9 mt/ha/year sweet potato yields at Kahikinui to separately estimate the carrying capacity for a population requiring 2000 kcal/person/day. He used a definition of carrying capacity that relates to the maximum conversion of expected food supply into people, without discounting for wastage, exchange, animal feed, tribute, or the significant effect of variability in food supply. He found the density at carrying capacity would have been 174 persons/km^2 in the occupied (agricultural) zone, concluding that although it probably significantly overestimated population, the exercise was useful in confirming that the numbers of the archaeological estimate could have been supported on the resources that were available to them. Ladefoged and Graves (2007) estimated 139.4 persons/km^2 from archaeological features in a 112 ha detailed study area in the midst of the expansive dryland agricultural system of the Kohala Peninsula (Hawai'i Island). Kirch (2010) estimated roughly 262 person/km^2 for prime agricultural land across the whole island of Hawai'i, arguing that the value was a reasonable one for intensified dryland areas on the archipelago. Hamilton and Kahn (2007) estimated a minimum density in the 'Opunohu Valley of Mo'orea, French Polynesia, of 52 persons/km^2 based on archaeological features, and 87 persons/km^2 in the area of greatest occupation and use, although the population may still have been growing at the time of contact. Taken together these studies suggest that a density of about 50 persons/km^2 of agricultural land should be a reasonable minimum and 250 persons/km^2 a reasonable maximum. If we apply these densities to the estimate of 3134 ha of agricultural space on Rapa Nui, we get a low of 1567 people and a high of 7835 people for Rapa Nui.

Can these estimates be reconciled with the results of the Bayliss-Smith and space-limited approaches for Rapa Nui? Well, easily, if we assume the low-nitrogen scenario. But we already suspect it may be too conservative with regard to sweet potato yields, as we know the Rapanui grew sugar cane of the variety that boosts plant-available nitrogen as it decomposes. Both modeling approaches work from a form of ecological carrying capacity estimate, in which the maximum yield is assumed to be available. And much can happen along the way as we work from hypothetical yields to the human populations that need actual yields to live. Bayliss-Smith (1974) found that the actual population was some 70–80% of the estimated carrying capacity. Bellwood (1971, 1972) concluded that only 50% of the estimated maximum yield in valleys in the Cook Islands and Marquesas was actually produced. Hamilton and Kahn (2007) estimated that the archaeological estimates of the population of Mo‘orea were only 11% of the carrying capacity. Explanations for the discrepancies between carrying capacities may lie in overestimates of realized production, either due to an overestimate of the quantity or quality of agricultural land. As described in the previous section, the effect of expected variation in the food supply is known to be powerful, but is generally unaccounted for. Then there are the behavioral factors to consider. Bayliss-Smith allows us to examine the consequences of different expectation of labor inputs, and it is possible in places like Rapa Nui that the working population either chose not to work very many hours or competing obligations reduced the hours they had available. This possibility is supported by Roggeveen’s observation that good land appeared to be unused, as if left fallow in a less-intensive agricultural regime. Fertility control (including infanticide) could similarly reduce the equilibrium population, as a matter of individual choice or societal pressure.

9 Conclusions

Our goal has been to examine the meaning and role of carrying capacity as it applies to subsistence agrarian populations of the Pacific. The first, and perhaps most important, conclusion is that the term “carrying capacity” itself has no single meaning and comes burdened with its own baggage. We find the concept of a carrying capacity to be a useful one, but that utility is easily eroded by imprecise language. We favor the manner in which Bayliss-Smith (1980) uses it, representing an estimate of the maximum number of people who could be fed in a particular place given the location’s ecological characteristics and the population’s technology. This estimate is an intermediate stopping point on the way to a more nuanced consideration of reasonable population sizes. The second point is that attempts to estimate carrying capacity, without good ecological and cultural information, might be an empty endeavor. In the case of Rapa Nui, we can consider several scenarios. The range of estimates of sweet potato yields in Oceania before European contact encompasses the yields we use here: approximately 1.5 to 5.1 metric tons per hectare per year under continuous cultivation. But the populations that might have lived on those yields on Rapa Nui, after considering several important qualifiers, range from approximately 5000 to 25,000. We do not argue that either population number is supported by this exercise. We do argue that the result depends largely on whatever yield the Rapanui were actually able to achieve and, additionally, how variable that yield was. The impact of sugar cane mulching in elevating N levels and productivity is key, and unfortunately, we do not know the extent to which this was practiced. It is highly encouraging, however, that two different models of maximum population size agree so closely in their predictions, despite quite different conceptions of human welfare and its role in population regulation. Ultimately, we find that although ecological characteristics can constrain a population's size in important ways, cultural and behavioral attributes can reduce its expected size well below the theoretical maximum.

Acknowledgments We thank Sonia Haoa, Chris Stevenson, Oliver Chadwick, Peter Vitousek, and Pat Kirch for their help and collaborations. We also thank Bruce Winterhalder and Virginia Matzek for helpful comments on an earlier draft of this chapter. This research was partially funded by grants from the National Science Foundation (CNH-1313830 and BCS-0911056) and the University of Auckland, with the support of Te Pūnaha Matatini.

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Chapter 21
Population Principles, Climate Change, and the “Collapse” of the Rapa Nui Society

Mauricio Lima, Eugenia M. Gayo, Sergio A. Estay, and Nils Chr. Stenseth

1 Introduction

The agrarian society’s dynamic from Easter Island (Rapa Nui) and its apparent collapses has fascinated scholars for several decades, although societal demises have been described in other places and times. The phenomena of societal collapses have been highlighted as recurrent events in Humankind history triggering a growing concern for identifying convergences/divergences among different cases to explain tipping elements and points between breakdown or resilience. Still, collapse is a general term with different meanings leading to a heated debate in the scientific community. In general, the concept has been applied to different entities such

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_21

as states, nations, or complex societies, and how they can arise and decline. However, in most of these studies, the variables involved are diverse, such as sociopolitical organization, economy, environment, and population size (Butzer 2012). For instance, Tainter (1988) defines collapse as a political process related to a rapid sociopolitical complexity loss. Conversely, collapse can be viewed as a population process characterized by negative population growth rates that impact several generations. In this sense, such process should be referred as demographic collapses (Meadows 2004). Both definitions, however, are not necessarily exclusive. Sociopolitical collapses could arise without major demographic consequences. Indeed, both processes usually interact, generating a concurrent loss of sociopolitical complexity and population declines (e.g., Lee and Zhang 2010; Turchin 2009).

Past agrarian societies can provide unique natural, socio-ecological laboratories for testing different hypotheses explaining how the interaction between ecological factors, climate, and human population can lead to societal collapse. The relationship between human population dynamics, food production, and climate change is an ancient problem in human societies, especially in agrarian societies, with profound implications for current societal problems (Butzer 2012). For instance, Bevan et al. (2017) as well as Warden et al. (2017) showed how climatic conditions mediate changes in human population growth rates.

Assessing the role of ecological and climatic factors through the Population Dynamic Theory (PDT, Box 21.1) can often shed light on why demographic collapses happen by testing different hypotheses. The application of the PDT framework (Box 21.1) and all its methods borrowed from ecological theory is a powerful perspective to detangle links between climate variability and population dynamics of past societies. This is because formal modeling methods provide the means to test hypotheses rigorously and quantify the evidence supporting each of these (Berryman 1999; Royama 1992; Turchin 2003).In a simple first scenario, the relationship between population size and climatic variables could be represented as an additive effect in statistical models (Stenseth et al. 2004), a vertical perturbation where both equilibrium density and maximum reproductive rate change (Royama 1992). Nevertheless, climate effects have often been proved to be non-additive (Royama 1992) (Box 21.1). The first example of this non-additive effect is the so-called lateral perturbation (see Fig. 4c in Lima et al. 2020; Box 21.1). Here, exogenous forces modify only the equilibrium density, but the maximum reproductive rate remains unchanged.

Since in agrarian human populations equilibrium levels are usually set by crop productivity, we should anticipate lateral perturbation effects whenever climate or other exogenous factor is suspected of influencing food production/crop yields (Box 21.1). Hence, explanations of climatic effects on past agrarian societies need to consider the possible effects of climate on food production. Another related problem is that when the exogenous factor, such as climatic variability, influences a limiting resource, such as crop production, it is very likely that, in those cases, climate represents a lateral perturbation on the crop productivity itself. The problem with this kind of exogenous effect is that it affects the availability of some limiting factor or resource (e.g., food); hence, the per capita resource availability shared for the individuals is also influenced (Royama 1992). These non-additive effects are normally expected when the ratio (i.e., population/crop production) characterizes the per capita share of the resources and the competition strength, changing the limiting factor's availability. Under this scenario, small changes in a climate variable could have large changes in population growth rates because there is an interaction between climate, crop production, and population size resulting in potentially nonlinear responses of populations to changes in climate (Berryman and Lima 2006; Lima and Berryman 2006; Lima et al. 2006; Royama 1992). Therefore, the primary objective of this chapter is to analyze the Rapa Nui archeological data employing a simple approach to understand how climate affects human population dynamics. In this way, we propose an alternative view of the population changes of the Rapa Nui people.

Population changes of the Rapa Nui society have several causal explanations, receiving the most attention those invoking an anthropogenic-driven ecological catastrophe. This "ecocide hypothesis" assumes a punctuated demographic crash caused by the abrupt reduction and replacement of native palm forest by grasslands, ultimately driven by unchecked population growth coupled with social fractions and friction as crop productivity decreased (Diamond 2005; Flenley and Bahn 2002; Rolett and Diamond 2004). In contrast, the "genocide hypothesis" emphasizes violence, slaver raids, and epidemics introduced shortly after European contact in the early eighteenth century (Hunt and Lipo 2006; Hunt and Lipo 2009). Proponents of this genocide hypothesis suggest that Rapa Nui populations did not decline until the European colonization (1722 CE). Alternatively, Rull et al. (2013) emphasize the socio-ecological resilience and identify a first societal crisis (1450–1550 CE) linked to hydroclimate–cultural synergies. Meanwhile, the occurrence of two population downfalls is recognized after 1722 CE (Rull et al. 2013).

Although these explanations constitute major advances in understanding Rapa Nui's history, none of these scenarios have been evaluated using models that integrate hydroclimate and demographic data as independent sources of information to portray the local socio-ecological systems. This chapter is dedicated to exemplifying the power and feasibility of the PDT perspective for analyzing and interpreting past human population dynamics, specifically in Rapa Nui. We review the framework adopted in Lima et al. (2020) to test and integrate explicitly coupled agencies and cascading feedback between climatic, demographic, and ecological factors that affected the Rapa Nui people's trajectory. In particular, in this chapter we develop in detailed way how climatic perturbations acting on the agricultural land carrying capacity can be included in population dynamic models for proposing a formal hypothesis of socio-demographic changes in Rapa Nui people.

Box 21.1 The PDT Framework

The classical PDT proposes that climatic variability will affect the long-term food production or crop yields, affecting the equilibrium density (also called carrying capacity) of a given agrarian society. Thus, let k will be set by the amount of land available for agriculture and the current agrarian technology (yields per unit of area), which represents the limiting resource base for an agrarian society. A simple population dynamic model for this system is:

$$P_{t+1} = \frac{R_{t+1}}{R_{max}} = 1 - \left(\frac{N_t}{a \cdot k}\right), \tag{21.1}$$

Here R_{t+1}, is the realized per capita population growth rate over a given interval of time with $R_{\max}$ being the maximum possible rate. Hence, P_{t+1} measures the relative growth rate over a particular period of time. Note that the maximum per capita rate of increase $R_{\max}$ defines the maximum per capita birth rates (B) and minimum per capita mortality rates (D) (Berryman 1999). The expression on the right of Eq. 21.1 defines how the average individual fitness changes in relation to the size of the population N and the rate of renewal of an essential limiting resource k, with a being the unit value of that resource (arable land/crop yield). This can also be thought of as the relative “biological fitness” or “standard-of-living” or “well-being” of an average individual in the population. This equation predicts that individual performance will decline in proportion to the size of the population (or social structure), all else being equal. The term on the right of Eq. (21.1) defines the relative degree of competition for a limiting resource, expressed as a function of the density (or concentration) of humans per unit value of land productivity. It is not too difficult to see an economic analogy in the demand of a population N for a supply of resources k.

As the population increase in size, all available resources will be used (k), for example, cultivable land. Further increase of population numbers immediately (without time lags) results in lower average consumption rates. Since there is no time lag, there should be no over-shoot of the carrying capacity. However, these societies may face long-term climate changes that may shrink the land available for agriculture or the yield per unit of area (k) or the unit value of the crops (a). The explanation relies on the combination of Malthusian theory (Malthus 1798) with climatic variability as an exogenous forcing factor. Climatic variability determines agricultural land carrying capacity, which affects the population growth of agrarian societies (Lima 2014; Zhang et al. 2007; Zhang et al. 2011). Lateral perturbations result from exogenous factors, like climate, acting on the limiting resource availability or renewal rates (Berryman 2004; Royama 1992) and causing non-additive effects. These non-additive effects on net fertility, mortality, or both are a

(continued)

Box 21.1 (continued)

function of climate through resource limitation. For example, an unfavorable climate could reduce fecundity due to energetic limitations, or mortality in infants or elders increases due to food acquisition constraints. As equilibrium population sizes are usually set by a resource in short supply (food production or crop yield), it is possible to anticipate lateral perturbation effects whenever climatic variability is suspected of influencing food supply. These non-additive effects are normally expected when the ratio (i.e., population/crop production) characterizes the per capita share of the resources and the competition strength, changing the limiting factor's availability. Under this scenario, small changes in a climate variable could have large population growth rates because there is an interaction between climate and population size (Berryman and Lima 2006; Lima et al. 2006; Royama 1992). Consequently, the climatic variable's effect cannot be evaluated independently of the population size because the exogenous effect (climate) acts in conjunction with population size (Berryman and Lima 2006; Lima 2014; Lima et al. 2006; Royama 1992). The dynamics of this system can be easily defined as a logistic equation with lateral perturbation effects (Royama 1992):

$$P_{t+1} = \frac{R_{t+1}}{R_{max}} = 1 - \left(\frac{N_t}{a \cdot C_t}\right), \tag{21.2}$$

Let P_{t+1}, R_{t+1}, R_{max}, N_t, and a being the same dynamic variables and parameters from eq. 21.1, but the limiting resource k is replaced by a dynamic variable represented by C_t, the climatic changes influencing the food production. In fact, previous studies have hypothesized that "food supply per capita" is the key variable driving population collapses in pre-industrial societies (Zhang et al. 2011). Under this model, the mechanism for explaining the population collapses is the direct link between long-term climate and land productivity (Lima 2014; Nefedov 2013; Zhang et al. 2007). Although social scientists have been discussing the role of Malthusian factors in shaping human population dynamics (Lee 1987; Lee and Anderson 2002), few studies have attempted to model environmental fluctuations (climate) as a lateral effect that directly affects the limiting factors in the long term (food production) (but see Royama 1992).

2 Putting Rapa Nui Population Changes into the Test through the PDT Framework

We propose a population dynamic model to evaluate expected predictions from a climate-ecology-demography dynamic. We used the summed probability density

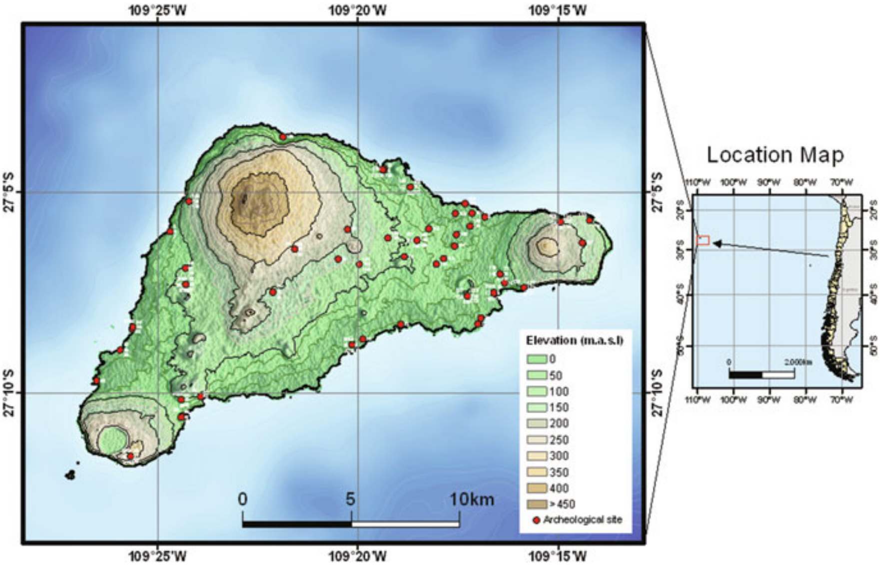

Fig. 21.1 Location for 91 archeological sites and 244 radiocarbon dates considered in this study for inferring paleodemographic trends in Easter Island. White numbers indicate the exact location for each ^{14}C-date. Note that considerable overlap exists between these data

(SPD) as paleodemographic proxy-data (Freeman et al. 2018) obtained for 244 radiocarbon dates from 95 archeological sites (Lima et al. 2020) (Fig. 21.1). Albeit the chronology for initial Polynesian colonization of the island is still a matter of debate, the oldest and youngest cultural radiocarbon dates considered here are 1180 ± 230 ^{14}C yr. BP (890 CE) 125 ± 30 ^{14}C yr. BP (1850 CE), respectively. Hence, we generated a 960-year time-series by summing the normalized posterior densities of these ^{14}C-dates in the R's carbon package (Crema and Bevan 2020). Further details on statistical procedures for controlling biases inherent to SPD reconstructions are presented in Lima et al. (2020). Before fitting models, the resulting SPD time-series were sectioned into time-step intervals of 30 years since 890 CE. With this procedure, we aimed to capture large population patterns and reduce high-frequency noise sources of variability.

Since the positive cold phase of El Niño Southern Oscillation (ENSO) is capable of reducing annual rainfall in Rapa Nui (Gallardo et al. 2016; Lima et al. 2020), a 2000-year reconstruction for the SOI index (Yan et al. 2011) serves as a proxy for ENSO-driven local hydroclimate anomalies.

In practice, the genocide scenario predicts that after the initial colonization, the population grew exponentially until an equilibrium population size determined by land area and crop/food productivity (Mann et al. 2008; Mieth and Bork 2010; Polet and Bocherens 2016; Rull et al. 2015). This scenario is described by eq. 21.1 with a constant or fixed renewal rates of the limiting resource k. On the other hand, the interplay between climate and demography (eq. 21.2) leads to a dynamic in that the island’s human population’s growth rate depends on the combined effect of recurrent droughts and ecosystem losses brought by large demographic levels. In turn, as negative rainfall anomalies progressed, human population sizes decreased gradually. Such synergic scenario for the human (N) population was described with a negative relationship of limiting resources (crop productivity) and the Southern Oscillation index values, high SOI values represent less annual rainfall (Lima et al. 2020). Therefore eq. 21.2 can be expressed as:

$$P_{t+1} = \frac{R_{t+1}}{R_{max}} = 1 - \left(\frac{N_t}{a \cdot \frac{1}{SOI_t}} \right), \tag{21.3}$$

Therefore, eqs. 21.3 and 21.1 can be used by fitting simple linear regression models to compare both hypotheses. Our starting point is to use the *R*-function (Berryman 1999) as a central element for connecting the model and quantitative paleodemographic, vegetational, and paleoclimate data. The realized logarithmic per capita population rate of change for a given interval of time can be estimated from a time-series data as the difference between the natural logarithms of population sizes *N*, $R_{t+1} = log\ N_{t+1}$ - $log\ N_t$, where N_t is the human population size (SPD data) at time t (Turchin 2009), and the realized relative per capita growth rates P_{t+1} are estimated as the ratio R_{t+1}/R_{max}, where R_{max} is the maximum observed growth rates.

Plotting P against the initial SPD values gives us the simple relationship predicted by eq. 21.1 for a constant limiting resource *k*, although the linear negative slope indicates the necessary and sufficient conditions for population regulation (Berryman et al. 2002), it is suggestive from Fig. 21.2c, that the limiting resource supply (crop productivity) could be fluctuating in time, causing changes in the equilibrium population sizes (blue arrows, Fig. 21.2c). However, when the data are expressed as eq. 21.2 the ratio of population size/limiting resources, we find that the relationship can be expressed by a simple negative linear regression model with a very good fit (Fig. 21.2d). As described in Lima et al. (2020), the role of hydroclimate changes and its impact on Rapa Nui people’s population size gets its better representation through models including lateral effects. These results give support to the hypothesis that relates population dynamics, including population collapses, to a complex interaction of climate, farming, and human population. Also, these results emphasize the strong non-additivity of this interaction (Fig. 21.2d).

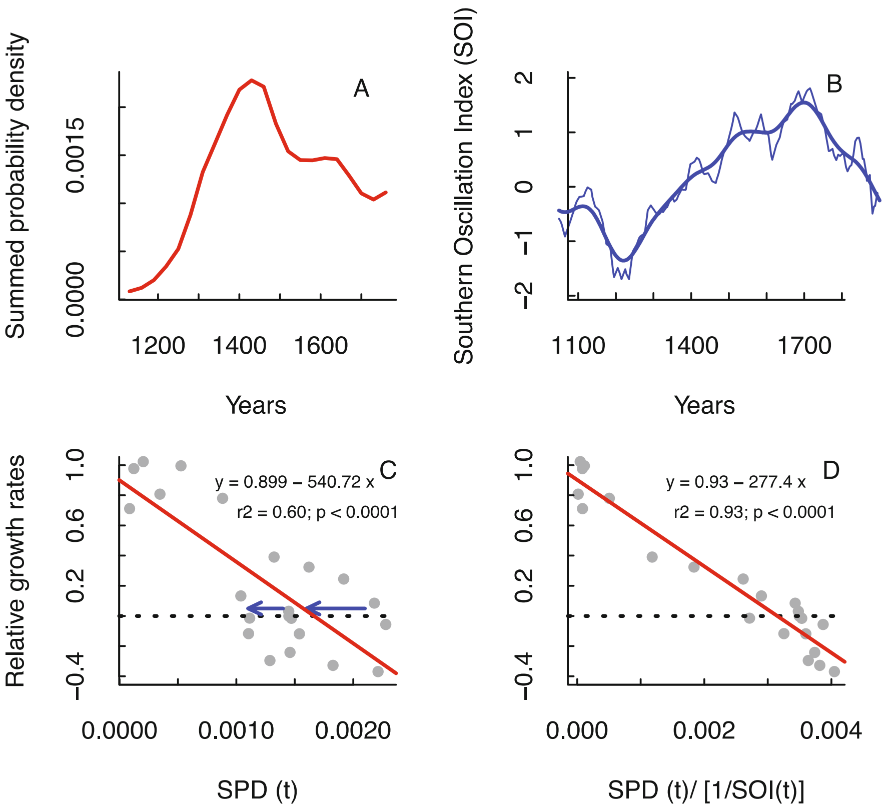

Fig. 21.2 (**a**) Reconstructed Summed Probability Density (SPD) for Rapa Nui (red line). (**b**) Southern Oscillation Index reconstruction (SOIpr) annually resolved (blue thin line) and smoothed time-series. (**c**) Relative per capita growth rates ($P_{t+1} = R_{t+1}/R_{max}$) plotted against the reconstructed SPD (one generation before = 30 years). Blue arrows indicate equilibrium population sizes during two declines. (**d**) Relationship between per capita relative growth rates (P_{t+1}) and the SPD by the unit of the Southern Index Oscillation for the same period. Text in the plots are the fitted linear regression model statistics

3 The Dynamics of Rapa Nui People

The application of the PDT framework for studying the Rapa Nui demographic trajectory suggests that long-term variations in ENSO activity can modulate the island's carrying capacity. Rapa Nui society's observed population dynamics is consistent with the hypothesis of non-additive long-term effects of ENSO variability on crop productivity (Stevenson et al. 2015). Evidence presented here and in Lima et al. (2020) suggests that population crashes in Rapa Nui arise from the long-term impact of hydroclimate change on the local carrying capacity, but more specifically on the "per-capita food supply" (Royama 1992). In fact, it is possible to link the role of hydroclimate change to the extensive deforestation that underwent in the island through the demand for farming lands, also linked to soil erosion and exhaustion. In the same sense, these intensified agricultural activities could have accelerated palm forest loss after 1200 CE [21]. This interplay between population size, long-term climate variability, and carrying capacity explains other populations collapses (Lima 2014)**.** By this means, the long-term direction trend between 1250 and 1700 CE (represented by the positive trend of the SOI index; Fig. 21.2b) might have led to a slow but persistent and cumulative reduction in the island’s crop productivity. Nevertheless, it is important to state that we are dealing with indirect proxies of human population size, crop production, and social complexity and our results are far from a definitive explanation.

The role of hydroclimate fluctuations on the island ecosystem services and demography has been debated (Diamond 2007; Junk and Claussen 2011). Nevertheless, severe negative hydroclimate anomalies during the Little Ice Age (LIA) have been associated to cultural and demographic changes in Rapa Nui (McCall 1993). We add up that the island’s demographic changes were indeed related to decadal fluctuations in ENSO activity that also affected other Eastern Pacific regions (Conroy et al. 2008; Morales et al. 2020). Furthermore, we evince that the impact of hydroclimate conditions on limiting factors was adjusted by population size (non-additive effects) via the effect on the per capita resource share (Royama 1992). This dynamic, however, operated independently on the magnitude or intensity of droughts. This implies that even small changes in a relevant climate factor—in this case, water supply—might generate disproportional demographic crashes if the population approximates its equilibrium size. Conversely, less pronounced demographic changes are expected when such populations experience the environmental change during the phase of exponential growth (Fig. 21.2c). A logical corollary for this is that the potential role of climate in driving demographic changes cannot be explained without including the role of population sizes.

Understanding feedback relationships between human population dynamics and climate change emerges as an urgent need for envisioning a sustainable future for human societies under the ongoing environmental crisis (Costanza et al. 2007; Cumming and Peterson 2017). In this vein, we demonstrate that the PDT offers a simple tool to test formal predictions and explanations for past demographic changes in Easter Island. Our results suggest that Rapa Nui society’s demography seems to be coupled to a gradual reduction in the water supply (rainfall) and productivity loss which seem to be consistent with archeological, ecological, and paleoclimatic data (Cañellas-Boltà et al. 2013; Mann et al. 2008; Mieth and Bork 2010; Rull et al. 2013). Well beyond previous controversies (Lima et al. 2020)—Rapa Nui people appear as an agrarian society that inhabited a small and isolated island and faced resource scarcity, overpopulation, and climate change as many others (Tainter 1988).

We believe that more productive than asking whether the Rapa Nui society collapsed or not, it is to formulate a classical population dynamic question, what causes the population and societal changes in the long term (Royama 1992; Taylor and Tainter 2016). Our results suggest that the long-term changes in the population size are a response to gradual increases in La Niña conditions (less rainfall) that could be closely linked with the observed ecological (deforestation) and socio-cultural (transition from moai cult to the birdman cult) transformations of the Rapa Nui society (Nunn 2007; Rull 2016). Increases and declines in population size and/or social complexity are changes commonly observed in human societies, and they are closely linked with processes of cooperation, competition, limiting resources, and problem solving (Taylor and Tainter 2016). Considering that overpopulation and global changes in temperature and precipitation regimens represent latent threats for modern and future human societies, we feel that the historical trajectory described here for Rapa Nui provides important insights on food security and ecological resilience.

Acknowledgments This work was funded by FONDECYT #1180121, ANID PIA/BASAL FB0002, FONDAP/ANID 15110009 and ANID–Millennium Science Initiative Program—NCN19_153. This study was undertaken by the PEOPLE 3000 working group of the Past Global Changes (PAGES). We thank to one anonymous reviewer that has substantially contributed to the quality of the final draft.

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Chapter 22
Claims and Evidence in the Population History of Rapa Nui (Easter Island)

Carl P. Lipo, Robert J. DiNapoli, and Terry L. Hunt

1 Introduction

For over 100 years, Rapa Nui (Easter Island, Chile) has presented a challenge to researchers seeking to explain how nearly 1000 multi-ton statues carved and transported across this tiny and remote island by a population that, at least at the time of European observation in the eighteenth century, were no more than a few thousand in number. Adding to the mystery is the fact that Rapa Nui is notably barren in terms of natural resources: the island lacks forests, running streams, and large-scale cultivation. For European observers, the island's state at the point of contact presented a stark contrast, a paradox. On the one hand, the island boasts a large number of massive prehistoric statues (*moai*) and monuments (*ahu*), indicating that islanders made incredible investments in labor and organization. On the other hand, the island appeared to lack a large number of people and available resources assumed necessary to produce this magnitude of monumentality. Rapa Nui's remarkable archeological record has, ever since, called out for an explanation.

For some observers, an answer was easily provided by imagining that conditions on the island were far more prosperous in the past. Starting with eighteenth-century visitors, speculative narratives emerged about the impacts islanders had on their environment. Many of these accounts are based on the assumption that the island was once more productive and that some previous event transformed it into its

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_22

current state. Johann Reinhold Forster (1777, cited in Hoare 1981, pp. 475–476), the naturalist who accompanied James Cook on his voyage to Rapa Nui in 1774, reasoned "either a civil or external war, a great mortality, too great luxury, or some other disaster reduced those Islanders to the small number we found them to be of." His son, Georg Forster (*apud* Jakubowska 2014, p. 86), reasoned that a volcanic eruption must have decimated the island; "it is very likely that one of those big, terrible natural disasters suddenly buried a great number of inhabitants." La Pérouse (1807, p. 4), for example, reasoned that the demographic and environmental conditions were due in large part to the "the imprudence of their ancestors" who cut down the island's trees (see also La Pérouse, 1807, p. 26). Some of the accounts are quite fanciful. Macmillan Brown (1924), for example, argued that the island is just a remnant of much greater "civilization" that supported massive populations but later sank beneath the ocean.

Over the past hundred years, visitors and researchers have speculated on the number of people the island may have supported in a previous state. These numbers have varied from estimates as few as 3000 (Meyer and Jablonowski 1901) to speculations as high as 57,500 (Routledge 1919, p. 215; Bahn and Flenley 1992, p. 170). Most of the contemporary numbers for the island's past maximum population size range between 10,000 and 20,000 people (e.g., Bahn and Flenley 1992; Flenley 1993; Diamond 1995, 2005; Puleston et al. 2017). These larger population sizes for Rapa Nui are often taken for granted and treated as fact. Borrowing from Elias (1958), this "population fact" has led to the production of many publications we can generically fit into two titles.

The first paper has the generic title "Mathematical Models of Demographic Collapse on Easter Island" written by a mathematician, economist, or population demographer; individuals who have neither conducted primary research about Rapa Nui nor have an appreciation for the challenges of using information from the archeological record in analyses. This paper tends to cite popular literature, assume chronologies long discarded by archeologists working on the island, and never involve evaluating hypotheses using archeological data. Instead, it uses Rapa Nui as an example of a mathematical model that illustrates why demographic collapse had to have happened, usually via a variant of a Malthusian model. The article invariably assumes the "population fact" and presents the island's demography using "boom and bust"-type graphs common in this kind of work. The graphs boast convincing dates on the x-axis and definitive population sizes on the y-axis, making them appear fully qualified, empirically determined, and validated. The math behind these models is sophisticated and illustrates how population peaks might have occurred if indeed all the assumptions about the island are, in fact, correct. The production of this kind of paper has become somewhat of a cottage industry in disciplines outside of archeology (Brander and Taylor 1998; Dalton and Coats 2000; Erickson and Gowdy 2000; Reuveny and Decker 2000; Pezzey and Anderies 2003; Basener and Ross 2004; Decker and Reuveny 2005; Good and Reuveny 2006; Basener et al. 2008; Bologna and Flores 2008; De la Croix and Dottori 2008; Uehara et al. 2010; Brandt and Merico 2015; Merico 2017; Roman et al. 2017; Basener and Basener 2019).

The second paper is typically called something like “Environmental Change Correlates with Collapse on Easter Island” and is written by an anthropologist, ecologist, or palynologist. There are two variants of these kinds of papers. One variant is authored by someone who has a general knowledge of Rapa Nui from a subset of published sources (e.g., Kirch 1984; Ponting 1991; Diamond 1995; Bahn 2015). The articles typically offer no new primary data but instead weave uncritical interpretations of previous publications together to make their case. The second variant views the island from the lens of environmental data, such as the sediment cores taken from one of three sites on the island: Rano Kau, Rano Aroi, or Rano Raraku. The paper then focuses on vegetation changes or climate records to create narratives about environmentally-induced cultural and demographic changes. The paper begins and ends with the overall assumption that the island has undergone population decline or profound cultural changes before the arrival of Europeans and seeks to determine the degree to which environmental factors may have played a role (e.g., Flenley et al. 1991; Pakandam 2009; Stenseth and Voje 2009; Rull et al. 2013, 2018; Rull 2016, 2018, 2020; Lima et al. 2020).

It is not our intention here to explore explanations for why assumed demographic changes might have occurred on the island, whether driven by climate, lack of resources, or some other factor. Rather, we focus on the common assumption held by both types of articles: at some point in the past, Rapa Nui hosted a population that significantly exceeded the small number of people observed at the time of initial European contact in AD 1722. In this paper, we evaluate the many claims that have been made about the pre-contact population sizes and examine the bases for these numbers. We divide these numbers into three categories: those based on speculation, those based on explicit models, and those based on historical observations. We conclude with an evaluation of the current empirical evidence that exists to support pre-contact population numbers.

2 Claims of Pre-Contact Population Sizes

Many of the early writers commented on the likelihood that the past population of Rapa Nui was not much greater than that observed by the earliest visitors. In 1774, John Reinhold Forster (*apud* Jakubowska 2014, p. 80) noted roughly 900 people, but also concluded that the number was since the arrival of Europeans: “therefore I conclude that either the number of inhabitants decreased over fifty years from various thousands to 800 or 900 individuals. Observing the island in 1869, Roussel questions whether the island was ever greatly populated stating (*apud* Lee et al. 2004, p. 46) “I have trouble believing that the population was as high as five or six thousand, as some of the natives insist. The interior of the island has never been settled ... Only the shore was inhabited and the clusters of *maute*, *toromiro,* and *hau* that are scattered about suggest a population of no more than five thousand souls with an average of five or six people per hut.”

In one of the first explicit discussions of the island's past population size, Thomson (1889) offers relatively sophisticated comments about the challenges of estimating population based on the archeological record since surface features and artifacts accumulate over time. Although lacking a means of estimating the time-depth, Thomson (1889, p. 460) notes that "the immense amount of work performed by the image-makers and platform builders would indicate the employment of a great many persons, if accomplished within a reasonable limit of time, or the extension over several centuries, if the undertaking was carried out by successive generations." Thomson (1889, p. 460) also considers the possibility that areas of settlement may represent mobile or seasonal occupation: "The ruins ... would prove either the presence of numerous inhabitants, or a frequent change of location. The limited area of the 32 square miles of surface available for cultivation precludes the idea of any very dense population, and many reasons might be assigned for a frequent change of habitation." As a result, Thomson readily accepts that the numbers were between 2000–3000 based on information from the Dutch, Spanish, English, and French accounts.

Other early accounts used numbers borrowed from other islands or generalizations made from estimates of what the island's terrain could support. The earliest example of this kind of reasoning is Meyer and Jablonowski (1901, p. 6), who use estimates of 13.7 individuals per square kilometer observed on Tahiti to claim that the island would have had "a population of 3000 people, and one will, in any case, have no room to go beyond this number as the upper limit." Routledge (1919, p. 215) notes that while earlier visitors consistently name just 2000 inhabitants, Percy Edmunds, the ranch manager on the island, suggests Rapa Nui could have supported more: "Mr. Edmunds calculates that about half of the total amount (or some 15,000 acres) could grow bananas and sweet potatoes. Two acres of cultivated ground would be sufficient to supply an ordinary family."

Skottsberg (1920, p. 488), visiting the island at the same time as Routledge, takes a more conservative view of the fertile capacity of the island and argues that "where there is sufficient soil this is of good quality and quite fertile when properly cultivated, and in prehistoric and early historic times extensive plantations existed supporting a population of several thousands." After his visit in the mid-1930s, Métraux (1940) used the land area required to support the island's residents as he observed them to calculate the total carrying capacity of the island. Metraux (1940, p. 22) states that "if 456 natives can live easily on a small portion of the island which is not particularly fertile it may be assumed that eight or nine times that number could have made a comfortable living on the entire island. Formerly fishing was a more important food resource than it is now. I believe that the population of Easter Island a hundred years ago must have been between 3000 and 4000."

Population estimates jumped considerably following William Mulloy's (1974) publication of "Contemplate the Navel of the World." Grounded in the growing awareness of the earth's limited ecological resources and alarmed by Ehrlich's (1968) book *The Population Bomb* predicting imminent massive global famines, Mulloy's (1974) article frames Rapa Nui's prehistory as an example of the dire consequences of population exceeding carrying capacity. While Mulloy does not specifically cite population figures, this article heralds the first time the concept of “overpopulation” is used in the context of Rapa Nui. He suggests that the growing population, coupled with the limits of the island’s resources, resulted in food shortages, precipitating a socio-economic crisis for the islanders.

Following this publication, the literature begins to include a greater emphasis on environmental degradation through deforestation caused by the needs of ever greater numbers of islanders. McCoy (1976, pp. 141–142), for example, rejects the smaller estimates by La Pérouse (1807) and Metraux (1940) and suggests that the island had a maximum population of 7000. His rationale is based on an assumption that much larger numbers than 3000–4000 were required to produce the island’s monumental architecture. Based on the comment by Edmunds recorded by Routledge (1919, p. 215) with 15,000 acres of arable land and 2 acres of land sufficient per family, McCoy (1976) argues the island might have had at least 7000 people. McCoy (1979, p. 160) emphasizes the impact that such a large population would have had on such a tiny island: “even if the maximum population was only 4000 to 5000, it is easy to envision the eventuality of near-total deforestation in a relatively short time, assuming that the early forest was indeed a savanna- parkland type formation of scattered trees and shrubs.” McCall (1976, p. 45) also posits a population peak that occurred before European arrival, adding that it was in AD 1500 that population increases and decreased rainfall combined to produce famine and the loss of food production capacity.

Stevenson (1984, pp. 172–173) substantially expands on these numbers using ethnohistoric estimates of family size from Hawai‘i and the number of residential archeological features identified during field surveys. Based on chronological determinations made using obsidian hydration dates, Stevenson suggests that the population density at ca. AD 1600 was 147 persons per square kilometer. Based on the assumption made by Routledge (1919) that no more than 50% of the island was suitable for cultivation, he then reasons that the population was 8927 in AD 1600 and then 9659 in AD 1800. Stevenson (1984) then reasons that these numbers likely underestimate the population due to denser habitation around Rano Raraku and that individuals also lived in cave habitations. Based on this reasoning, Stevenson (1984, p. 173) posits that the island’s peak population was 11,000–12,000 persons.

Ayres (1985) supports these relatively large population numbers. While he rejects Metraux’s (1940, p. 151) estimates as being too low, he also rejects his calculations that the maximum population would be between 37,500 and 52,500, numbers he arrives at based on Routledge’s (1919) note that the island’s 15,000 acres of arable land could support five to seven individuals per household using two acres for each family. Based on general observation of historic population sizes, Ayres (1985, p. 105) concludes that pre-contact populations are “realistically running up to 6–8000 people.”

By the mid-1980s, the idea that overpopulation was a major factor in the island’s pre-contact history had taken root. In 1984, we see the first emergence of the now-famous “collapse” narrative (Fig. 22.1). Though he offers no specific numbers, Kirch (1984, p. 264) characterizes the island as having a population that “temporarily but brilliantly surpassing its limits - crashed devastatingly.” Like

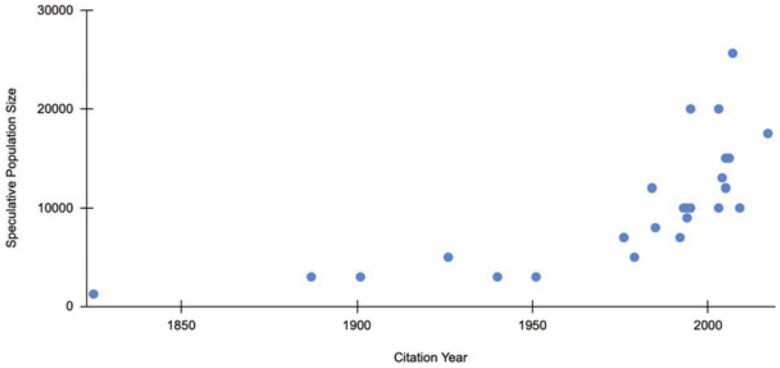

Fig. 22.1 Graphical representation for maximum pre-contact population size claims by citation year

Mulloy, Kirch (1984, p. 274) emphasizes environmental degradation as a major factor in social change in late prehistory and states "Easter Island had reached a state of over-population, which was the proximate cause leading to an ensuing phase of chronic inter-tribal warfare and social disintegration."

Ponting (1991) uses the work of McCoy to put forward a Rapa Nui collapse narrative in a popular context in his book "A New Green History of the World." Ponting (1991, p. 5) states that "the population of the island grew steadily from the original small group in the fifth century to about 7000 at its peak in 1550." Bahn and Flenley (1992, see also Bahn 1993, p. 54; Flenley and Bahn 2002, p. 170; Bahn and Flenley 2017, p. 218) utilize the high numbers quoted by others: "most archaeologists who have worked on the island in recent years estimate that the prehistoric population may have reached 6000 to 8000, while some speculate about figures of 10,000 or even 20,000" though they do not share where the 20,000 numbers might have originated. Diamond (1995) simply repeats the arguments made by Ponting, Bahn, and Flenley in his collapse narrative: "an estimate of 7000 people is widely quoted by archeologists, but other estimates range up to 20,000, which does not seem implausible for an island of Easter's area and fertility."

With these publications, a massive pre-contact population decline had become widely accepted as fact. Based on the summaries of others, Cohen (1995, p. 357), for example, provides his summary of the island's history: "the population remained low until about A.D. 1100. Growth then accelerated and the population doubled every century until around 1400. Slower growth continued until at most 6000 to 8000 people occupied the island around 1600. The maximum population may have reached 10,000 people in A.D. 1680." Loret (2003, p. 21) states "the densities of archaeological sites indicate a population greater than 7000; some archaeologists estimate it could have been up to 20,000." Kirksey (2003, p. 196) argues the island had "a native population that once numbered over 10,000." Foot (2004, p. 13) asserts that "the population peaked in mid-century at around 10,000 (+/–3000) people and then suddenly collapsed." Fischer (2005, p. 45) claims "On Easter Island itself, by the early 1700s the peak population of approximately 12,000 that might have been attained in the fourteenth and fifteenth centuries had perhaps shrunk." Pakandam (2009, p. 16) cites population sizes of 7000–10,000 based on claims made by Bahn, Flenley, and Stevenson to support his argument.

While many authors simply assume the large numbers cited by others (e.g., Pakandam 2009, p. 16), some attempt to use aspects of the archeological record to rationalize the values offered. Van Tilburg (1994), for example, made use of unpublished settlement pattern data generated as part of the Easter Island Archeological Survey conducted by Vargas Cassanova and Cristino to justify pre-contact population sizes (Vargas Casanova and Cristino n.d. 1997). Van Tilburg (1994, p. 67) states:

> Métraux recorded nine members per Rapa Nui family. If we multiply the 3244 house foundations known to date by nine, we arrive at the extraordinary population estimate of 29,196. At five family members, we still have a very high figure of 16,220. Many Rapa Nui shelters were recycled and reused, and it is not yet certain how many houses were contemporaneous, specialized, or temporary. A good rule of thumb is to reduce the population estimate by two-thirds. This gives us a figure of 9732 people (at nine per family) or 5406 at five per family. Considering the bulk of the survey evidence and the previous 7000 estimates of McCoy's research, a total population of between 7000 and 9000 people, or a gross density of between 44 and 56 people per square kilometer, is reasonable and in fact, somewhat low by Polynesian standards.

Vargas Cassanova and colleagues (2006, p. 300) follow a similar argument in their claim of more than 15,000 inhabitants, focusing their estimate on assumptions about the maximum agricultural productivity of the island in addition to house counts.

Diamond's (2005) popular book "Collapse" repeats claims by others and rejects the relatively conservative estimates of 6000–8000. Diamond (2005, p. 91) states "it seems to me impossible that the 1864 post-smallpox population of 2000 people represented the residue of a pre-smallpox, pre-kidnapping, pre-other-epidemic, pre-seventeenth-century-crash population of only 6000 to 8000 people. Having seen the evidence for intensive prehistoric agriculture on Easter, I find Claudio's and Edmundo's "high" estimates of 15,000 or more people unsurprising." Likewise, other authors simply assume high numbers based on claims made by others.

As shown in Fig. 22.1, the history of pre-European contact population size claims for Rapa Nui hovered largely between 3–5000 through the 1970s. It was only after the 1970s and the rise of contemporary concerns about global resource degradation and overpopulation that speculation about much larger population sizes began. Once introduced by Mulloy (1974) and McCoy (1976) and supported by claims made by Kirch (1984) and later Diamond (1995), these speculative numbers increase markedly and became the basis for many of the Malthusian narratives about the island's ecological and demographic collapse.

3 A Critical Review of the Evidence

While these population estimates are speculative, they follow several basic algorithms. The first set of estimates (e.g., Mulloy 1974; Kirch 1984, p. 274; Ayres 1985, p. 105; Ponting 1991, p. 5; Bahn and Flenley 1992, 2017, p. 217; Bahn 1993, p. 54; McCall 1994, p. 37; Cohen 1995, p. 357; Diamond 1995, 2005, p. 91; Flenley and Bahn 2002, p. 170; Kirksey 2003, p. 196; Loret 2003, p. 21; Foot 2004, p. 13; Fischer 2005, p. 45; Pakandam 2009, p. 16) is speculative and based on second-hand numbers and/or numbers assumed as "overpopulation." The reasoning here is circular as it relies on the a priori claim that the historic populations must have been far smaller than those that pre-dated European arrival. These population numbers are most closely associated with the "collapse" narrative.

3.1 Historic Observations

Rather than speculate about possible population sizes, we suggest a better starting position is gained by examining the currently available evidence. Among the most relevant are a series of eyewitness accounts recorded by the initial European visitors who observed and described conditions on the island beginning in the eighteenth century. As documented by Boersema (2015; Boersema and Huele 2019, Table 22.1), the earliest European visitors noted no more than 3000 people. In 1722, for example, Behrens (1737, p. 82, *apud* Boersema and Huele 2019, p. 84) notes that "the inhabitants were swimming around in their thousands." In 1770, Spanish observers (Corney 1903, p. xlv) report that the island's "natives number about 3000 of both sexes." In 1786, La Pérouse (1807, p. 26) concludes "the whole population may be estimated at two thousand persons." While each account may be based on just a sampling of the island, the earliest observations converge on the conclusion of about 2000–3000 people at contact (Boersema and Huele 2019).

3.2 House Count Estimates

The second line of evidence might be gained from counts of the number of residential features observed during field surveys (e.g., Thomson 1889, p. 460; Stevenson 1984, pp. 172–173; Van Tilburg 1994, p. 67). In this "house count" method, the number of domestic features identified through field surveys is multiplied by an assumed constant household size to yield a total population size. For Rapa Nui, this has been based on multiplying estimates of family size (e.g., between 5 and 9) by the number of residential units (e.g., Stevenson 1984, pp. 172–173; Van Tilburg 1994, p. 67). While changing intensities of domestic features actively in use can indeed provide a rough measure of demographic change, several issues

Table 22.1 Summary of claims for pre-European contact population sizes

Year	Citation	Number cited
1825	Beechey (1831:12)	1260
1887	Thomson (1889)	2000–3000
1901	Meyer and Jablonowski (1901:6)	3000
1926	Roussel (1926) (A. Atlman, Trans.)	5000
1940	Métraux (1940:22)	3000
1951	Skottsberg (1920:488)	2000–3000
1976	McCoy (1976:141)	7000
1976	McCoy (1976:142)	7000
1979	McCoy (1979:160)	4–5000
1984	Stevenson (1984:172–173)	11,000–12,000
1985	Ayers (1985:105)	7000–8000
1992	Ponting (1991:5)	7000
1993	Bahn and Flenley (1992) Bahn (1993:54) Flenley and Bahn (2002:170) Bahn and Flenley (2017: 218)	>10,000
1994	Van Tilburg (1994:67)	7000–9000
1994	McCall (1994:37)	10,000
1995	Diamond (1995)	20,000
1995	Cohen (1995:357)	10,000
2003	Loret (2003:21)	7000–20,000
2003	Kirksey (2003:196)	>10,000
2004	Foot (2004:13)	10,000+/−3000
2005	Fischer (2005:45)	12,000
2005	Diamond (2005:91)	15,000
2006	Vargas et al. (2006:300–301)	15,000
2007	Rallu (2007:22)	25,650
2009	Pakandam (2009:16)	7000–10,000
2017	Puleston et al. (2017: 10)	3500–17,500

preclude a straightforward reconstruction of past population sizes based on counts of surface domestic features (Drennan et al. 2015, pp. 14–16; Palmisano et al. 2017; Bevan and Crema 2021). The problems with the house counting approach center on determining the equivalence of the unit being counted (Bevan and Crema 2021), whether equivalence in time or equivalence of occupation characteristics (Drennan et al. 2015). For example, researchers have typically assumed a time equivalence for Rapa Nui domestic features in the sense that features found on the surface are contemporaneous. As Thomson (1889, p. 460) was astute in pointing out more than 100 years ago, the challenge with this approach is that it requires robust knowledge about the chronology of occupation.

House count-based demographic estimates for Rapa Nui assume that surveyed domestic features were actively in use at the same time. Mulrooney's (2012, 2013) analyses of the Hanga Hoʻonu region, however, clearly shows this cannot be the case and that structures were in use at different times. Stevenson (1984) attempts to address the chronological issue by sorting residential locations at the scale of *ahu* through time using obsidian hydration dates. It is unclear, though, how these dates relate to the contemporaneous occupation of individual structures. Without a high-resolution radiocarbon chronology directly related to deposit events for a large sample of these features from across the island, it is not possible to ascertain an absolute count of which 'houses' were inhabited at various times in the island's history.

Another unresolved issue is their assumed equivalence in terms of use duration (e.g., Drennan et al. 2015; Crema and Kobayashi 2020). If, for example, some domestic features are in use for a single human generation whereas others substantially more or less, then any demographic estimates based on equivalent duration would be strongly biased. While Bayesian radiocarbon chronologies could be used to estimate the span of domestic feature use (Bronk Ramsey 2009), such studies are largely lacking on Rapa Nui. DiNapoli et al.'s (2020b) Bayesian analyses of *ahu*, however, offer an example of how this work might be productively conducted.

An additional concern is the assumption of an equivalent and constant number of occupants per domestic feature across space and time. In his early twentieth century demographic work, Metraux (1940, pp. 97–98) divided the population of 456 Rapanui by the 50 houses in use to estimate an average of 9 individuals per household, though he notes there is no reason to assume this figure characterizes households in pre-contact times. If the number of house occupants was variable in time (seasonally, annually, decadally) and space, then an increase in one domestic feature is not directly proportional to a unit increase in population (see Bevan and Crema 2021). Lacking a fine-grained chronology of domestic features and assuming their equivalence in several domains, most previous house count estimates for Rapa Nui, therefore, remain questionable.

4 Resource-Based Estimates

The third line of evidence used to estimate population numbers considers what the island *could support* given potential agricultural productivity (e.g., Meyer and Jablonowski 1901, p. 6; Routledge 1919; Skottsberg 1920, p. 488; Métraux 1940, p. 22; McCoy 1976, pp. 141–142, 1979, p. 160; Vargas Casanova et al. 2006, pp. 300–301; Rallu 2007). While researchers acknowledge that historic population numbers were reduced due to disease, slave raiding, and other atrocities that took place after the arrival of Europeans (Fischer 2005), this approach typically uses productivity values extrapolated from observed settlement patterns for the island. The challenge in using productivity values is that the argument is based on generalizations about the amount of land used by a group of families at some point in a particular place. Some of the estimates (e.g., Bahn and Flenley 1992; Bahn 1993; Flenley and Bahn 2002) are particularly questionable as they largely rest on speculation by Routledge

(1919) that 15,000 acres of land could be put into use for agriculture in an equivalent fashion.

Additionally, there is an implicit assumption in population estimates based on resource abundance: that the actualized population size is a simple function of the absolute productivity of the land at any point in time. Even Malthus (1890) argued that reproduction is not determined solely by resource abundance. As Wood (1994, pp. 37–47, 1998, p. 104) notes, family size is driven by a host of factors that include risk tolerance, cultural traditions, rates of pregnancy loss, rates of maturation, and so on. While Malthus argued that populations tend to grow when food is abundant, the population size reached is not necessarily the maximum possible. The *possibility* of large populations does not mean that these populations were necessarily the case. In the case of the pre-contact history for Rapa Nui, only the assumption that the island must have been more greatly populated at one time, a proposition first raised in 1774, drives the conclusion that the numbers must have been greater. If we remove that assumption, it is no longer *necessary* to posit that the population was much greater than observed at European contact.

In a recent paper, Puleston et al. (2017) built a series of sophisticated food-limited demography simulations that combined ecological and demographic models with different agricultural productivity estimates to derive a range of estimates for potential peak population sizes on Rapa Nui. The outcomes of these simulations are strongly affected by varying the amount of bioavailable nitrogen (N) that could support crop growth. Because empirical estimates of N are limited for the island, Puleston et al. (2017) modeled contrasting scenarios, a "high-N" parameterization that resulted in mean maximum populations of ca. 17,500, and a "low-N" parameterization that resulted in mean populations of ca. 3500. While this modeling represents one of the most sophisticated attempts to estimate pre-contact population sizes, it lacks consideration of the effects of decadal-scale variability as well as sufficient N measurements to calibrate the model. As a result, there is no clear rationale why the high-N scenario should be preferred over the low-N versions (Lipo et al. 2018). One key piece of data that can be used for calibration, however, is the estimates of the first European visitors in the eighteenth century, who consistently note populations of ca. 3000 (Boersema and Huele 2019), indicating that Puleston et al.'s (2017) low-N estimate is most consistent with the available archeological and historical data (Lipo et al. 2018) and likely "is a better representation of pre-contact Rapa Nui than is the high-nitrogen scenario" (Puleston et al. 2018, p. 2).

4.1 Analyses of Summed Probability Distributions

Another approach has been to avoid estimating absolute pre-contact population numbers and instead examine the evidence for relative changes. Several studies have attempted to evaluate whether the pre-contact population was once much larger using summed probability distributions (SPDs) of radiometric dates (Mulrooney 2013; Stevenson et al. 2015; Lima et al. 2020). SPDs are a widely used method for examining relative change in past activity and are frequently used as a proxy for relative changes in population size (Crema and Bevan 2021). In a pioneering study for Rapa Nui archeology, Mulrooney (2013) compiled a dataset of all available radiocarbon dates from the island and used the most secure dates from settlement contexts to construct SPDs. Mulrooney (2013) then compared the empirical Rapa Nui SPD to a series of ad hoc curves for both population continuity and collapse ca. 1680 AD, a commonly claimed collapse date. Mulrooney's (2013) results did not show evidence of a pre-contact decline in the empirical SPD curve. In a similar analysis, Stevenson et al. (2015) conducted SPD analyses of obsidian hydration dates from settlement sites, finding no strong support for an overall major pre-contact decline in human activity. While their results did suggest potential spatial differences in land-use patterns over time, they concluded that "this temporal reconstruction of land-use history associated with food production argues against the notion of an island-wide precontact collapse as a useful explanatory concept for Rapa Nui" (Stevenson et al. 2015, p. 1029). Vargas et al. (2006, Figs. 6.1 and 6.2) also show temporal frequency plots of obsidian hydration dates that do not support the notion of pre-contact collapse (see also Stevenson and Williams 2018; Hunt and Lipo 2016). Moreover, Bayesian analyses of the chronology of *ahu* construction also show continuity in monument construction over time (DiNapoli et al. 2020b), contrary to previous collapse narratives (see DiNapoli et al. 2020a for a recent review).

In contrast to these previous studies, Lima et al. (2020) recently presented SPD analyses which they argue demonstrate a pre-contact population collapse for Rapa Nui. Their analysis is based on radiocarbon dates from settlement and ceremonial contexts coded as Class 1 and 2 by Mulrooney (2013), from which they constructed an SPD that appeared to have a large spike and decline after ca. 1450 AD. Lima et al. (2020) then fit four growth models directly to the SPD, including a simple logistic model with no assumption of collapse, and three additional models where carrying capacity can be reduced by deforestation, climate change, or a combination of these effects. They then compare the fit of these models and conclude that "Population analysis of the prehistoric Rapa Nui time series suggests that long-term climatic variability (e.g. SOI) and palm tree cover are proxies of the island's carrying capacity. A simple model appears to describe the dynamics of the human population in Rapa Nui quite well and can explain the increasing trend as well as population decline episodes that impacted during several generations, which we think can be defined as demographic collapses" (Lima et al. 2020, p. 7). These conclusions, however, are not valid for three important reasons: (1) selection of samples to include in the analysis; (2) normalizing the ^{14}C dates during calibration, and (3) directly fitting their demographic models to the empirical SPD.

First, in any analysis of radiocarbon dates, one must make a clear connection between the dated radiocarbon event and the target event of interest (Dean 1978). In the case of SPD analyses, the radiocarbon-dated events (e.g., death of the organism) must have a contextual linkage with the target event of demography, such as occupation deposits or other settlement sites (Mulrooney 2013; see Brown and Crema 2019). While Lima et al. (2020) did exclude the most problematic samples from their analyses (based on Mulrooney's [2013] chronometric hygiene), they did not consider this dated-event target-event relationship. While Lima et al. (2020, p. 7) correctly assert that dates from ceremonial contexts, along with the results in DiNapoli et al. (2020b) reflect "the 'continuities/discontinuities' in a given cultural tradition (i.e. the 'ahu moai' tradition), not a demographic process," they inexplicably included ca. 70 dates from these contexts in their analysis.

Second, a crucial concern is the consequences of ^{14}C normalization, which is a common step in radiocarbon calibration where the posterior density is normalized to one. While this is a reasonable step in calibrating single radiocarbon dates, when these dates are then summed to create SPDs, normalization causes spurious peaks at steep portions of the calibration curve (Weninger et al. 2015; Weninger and Edinborough 2020). For these reasons, one must either account for these artifacts of the radiocarbon calibration curve during any model fitting or simply choose not to normalize the dates when creating an SPD (Crema and Bevan 2021). Lima et al. (2020), however, did neither. Figure 22.2 shows the radiocarbon dataset used by Lima et al. (2020) with and without normalization along with the SHCal20 calibration curve (Hogg et al. 2020). The large peak observed by Lima et al. (2020) in the normalized SPD is an artifact of the steep portion of the Southern Hemisphere calibration curve, an issue Mulrooney (2013, p. 4382) also raised caution about in her original study. Once corrected for normalization, this spurious spike in the SPD is removed and evidence for "collapse" disappears.

Third, while Lima et al.'s attempt to compare the fit of multiple demographic models to the Rapa Nui SPD is hypothetically a useful approach, the attempt to directly fit these models to the normalized SPD has several problems: (1) they uncritically treat the sample size as the number of years in the analysis rather than the much smaller, correct sample size—the number of dated archeological contexts; and (2) they do not account for sampling error, measurement error, or the effects of the calibration curve, all of which can have a substantial impact on the shape of an observed SPD (Crema and Bevan 2021). Critically, because sampling error is not properly accounted for, the maximum likelihood estimates for their models are biased, and thus all other derived statistical results are incorrect and misleading (see Carleton 2021; Carleton and Groucutt 2020; Crema and Shoda 2021; DiNapoli et al. 2021; Stewart et al. 2021; Timpson et al. 2021 for similar criticisms). Essentially, Lima et al. (2020) have treated the SPD as a census of past population size rather than the idiosyncratic samples that they are.

When one adequately accounts for these sources of error and uncertainty, the results indicate opposite conclusions for Rapa Nui. DiNapoli et al. (2021) analyze the fit between an SPD of radiocarbon dates securely associated with Rapa Nui settlement sites and Lima et al.'s (2020) four logistic demographic models: (1) simple logistic growth, and three additional models that consider the effects of (2) changes in palm forest cover, (3) changes in the Southern Oscillation Index (SOI), and (3) a logistic model that includes both of these effects. Using an Approximate Bayesian Computation (ABC) approach to compare the fit of these four models to the Rapa Nui SPD that captures the uncertainty caused by sampling, measurement, and calibration errors, the results show that patterns in the SPD are

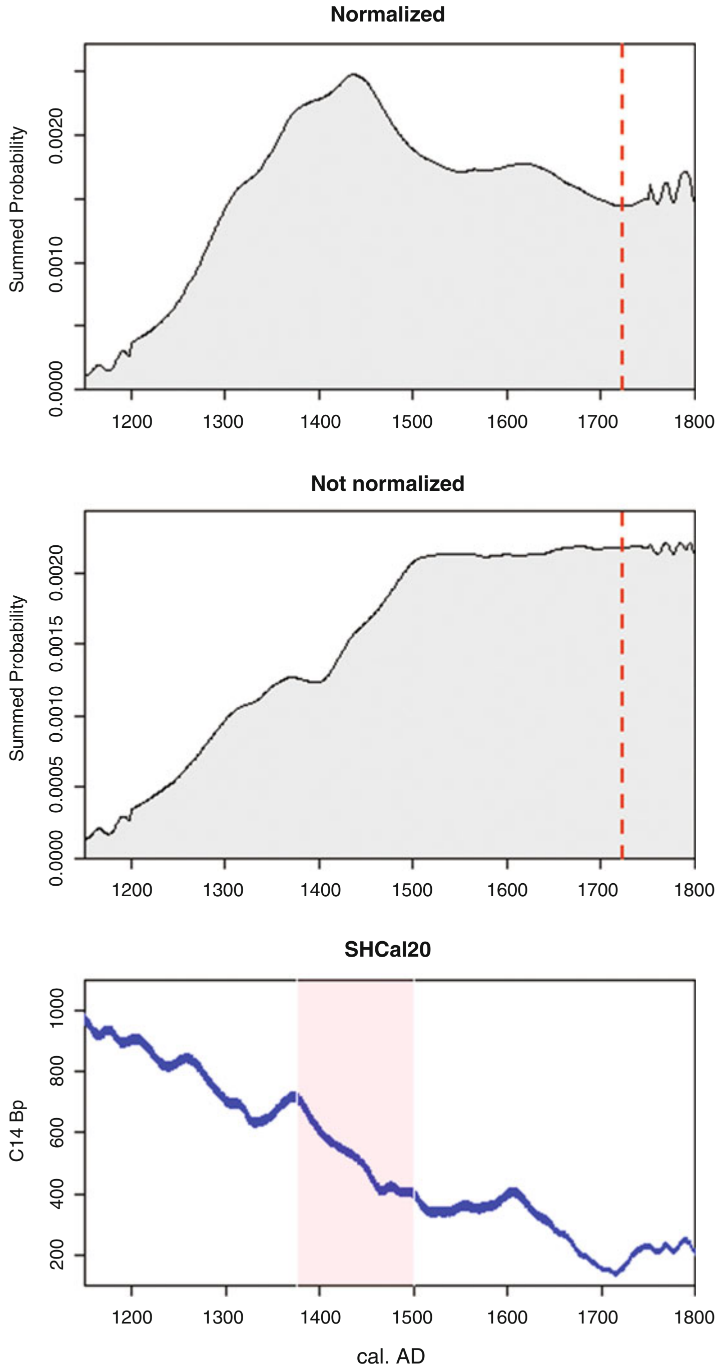

Fig. 22.2 Top: summed probability distribution (SPD) of normalized radiocarbon dates from Lima et al. (2020); Middle: the same SPD but with non-normalized dates; Bottom: the Southern

consistent with a logistic growth pattern (i.e., rapid initial growth followed by a plateau) and no evidence for a pre-contact demographic collapse (DiNapoli et al. 2021). Significantly, the results falsify previous claims that deforestation or SOI had negative demographic impacts on Rapa Nui and instead demonstrate that Rapa Nui people were resilient to any impacts from this environmental change.

4.2 Skeletal Age Distribution-Based Estimates

In an innovative evaluation of pre-contact population size on Rapa Nui, Boersema and Huele (2019) compared the age-at-death profiles of a human skeletal assemblage from Rapa Nui to published profiles for variation in rates of population growth. Boersema and Huele's (2019) results suggest that the osteological dataset they examined best fits a growth rate of ca. 0.5%. Assuming a maximum founding population size for the first Polynesian colonists of ca. 100 individuals, they conclude "a slow growing population in the pre-European period, which never exceeded 3000 people" (Boersema and Huele 2019, p. 90), a conclusion that fits the eyewitness accounts of eighteenth-century European visitors.

5 Conclusions

Beginning with the English and French accounts of Rapa Nui in the eighteenth century, scholars have long had an interest in Rapa Nui demography due to the extraordinary monumental architecture found on the island. Given the numbers and magnitude of *moai* and *ahu*, many visitors and researchers have assumed there must have been a much larger pre-contact population. From the nineteenth through the mid-twentieth century, though, population estimates consistently remained in the low thousands (Fig. 22.1). It was only after the widely influential publication of collapse narratives by Mulloy (1974) and Kirch (1984), we begin to see speculative estimates in the literature. These estimates increase exponentially through the 1990s and 2000s, with estimates as high as 20,000 people or more (e.g., Diamond 1995).

These large estimates are merely speculation, lacking any correlates in the archeological record, and indeed would require population growth rates unknown

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Fig. 22.2 (continued) Hemisphere radiocarbon calibration curve (SHCal20) for the period of interest (Hogg et al. 2020). The red shaded rectangle shows a particularly steep portion of the curve that results in a spurious spike in the normalized SPD used as the basis for Lima et al.'s (2020) analyses. The red vertical dashed line is the timing of initial European contact in 1722 AD. Note that these SPDs are based on radiocarbon dates binned by site in 50-year intervals and with a 100-year running mean for any other pre-industrial population (Boersema and Huele 2019). For example, a population in the tens of thousands on such a small island would be expected to leave traces of relatively dense, nucleated settlements, yet settlement pattern analyses show that Rapa Nui is characterized by relatively low-density and dispersed communities (e.g., McCoy 1976; see also Stevenson 1984; Stevenson and Haoa Cardinali 2008; Morrison 2012). Lacking a fine-grained chronology for a large sample of domestic features, absolute population estimates based on "house counts" remain problematic. Lima et al.'s (2020) recent SPD analyses tell us more about artifacts of the radiocarbon calibration curve than about pre-contact Rapa Nui demography (Fig. 22.2). Indeed, time series analyses of radiometric dates that properly account for issues of archeological context and radiocarbon dating uncertainties consistently show population stability and resilience in pre-contact times (e.g., DiNapoli et al. 2021; Mulrooney 2013; Stevenson et al. 2015; Vargas Casanova et al. 2006; see also Mulrooney et al. 2010). These results are also supported by Boersema and Huele's (2019) osteological analyses suggesting growth rates resulting in population size around 3000. A lack of evidence for a major relative decline in the pre-contact population also provides useful information for further parameterizing the demographic simulations presented by Puleston et al. (2017). In particular, because relative analyses do not suggest a large pre-contact demographic decline, and the contact era population was ca. 3000 (Boersema 2015, Boersema and Huele 2019), then Puleston et al.'s (2017) "low-N" models that estimate mean maximum population sizes of ca. 3500 are the best fit to the available archaological and historic data.

Assembled as a whole, we can evaluate these numbers in the context of our current understanding of the archeological record. Overall, we have no evidence of a substantial pre-contact decrease in population size. Instead, the existing archeological evidence points to a population that increased after European arrival in the twelfth century and then reached a relatively stable state in the early sixteenth century: a logistic growth pattern. This population size was maintained after this point until the arrival of Europeans in the early eighteenth century. Thus, the island's peak population was between 2000–3000 as observed by these early explorers. After that point, the history of the island is well-documented: populations ultimately declined in the eighteenth and nineteenth centuries with the impacts of disease, slave raiding, and other post-contact events. We echo the challenge recently given by Boersema and Huele (2019, p. 91)—researchers who insist on continuing to argue for a pre-contact collapse on Rapa Nui should avoid rehashing the same "population problem" and build stronger claims based on empirical archeological evidence. Based on this understanding and until new evidence becomes available, future researchers should avoid variants of the two papers we described earlier. Following the advice of Elias (1958), we suggest that we direct our energy and efforts to better understanding the archeological record of Rapa Nui.

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Part VI
European Contact

Chapter 23
The Human Giants of Easter Island (Rapa Nui)

Eighteenth-century Fake News and Its Significance for Understanding the Persistence of Present-day Myths

Jan J. Boersema

1 Introduction: The Written Legacy of the Dutch Expedition to the Unknown Southland (1721–1722)[1]

In the late afternoon of 5 April 1722, Easter Sunday, crew members on board the *Afrikaansche Galey* sighted an island in the Pacific. The discovery was greeted with joy. Could this be the sandy island off the coast of the long-sought Unknown Southland, mentioned by Edward Davis in 1687? They signalled it to the *Arend* and the *Thienhoven*, the other two ships of the Dutch Expedition, and Commander Jacob Roggeveen gave the island the obvious name of Paaseiland (Dutch for Easter Island). Roggeveen and the crew of the two accompanying ships did not see the island until the next day. This explains why 6 April is often mentioned in travel reports. In the days that followed the Dutch approached the coast, saw that fires had been lit on the island, met a man from Easter Island who had managed to swim to one of their ships, and finally went ashore with 134 men on Friday, 10 April. Shortly after their landing, some sailors in the rear of the group panicked and fired on the islanders, killing ten to twelve inhabitants. Roggeveen and the other captains were angry and the petty officer involved was called to account. Nevertheless, the expedition went ahead, and impressions of this exceptional island were recorded in official logs and travel accounts. The Dutch visit lasted only one day, and at the end of that same day, the three captains and three pilots concluded in a joint meeting,

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[1] For the sake of clarity, the publication details of all accounts of this expedition are listed in the references.

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_23

chaired by Roggeveen, that this island could not be the ‘sandy island’ mentioned in Davis’s travel accounts. Having navigated around the island just in case, they finally set sail again on the 13 April, on a westerly course.

Roggeveen may have gained some notoriety for being the first European to set foot on the now legendary island, but his expedition could hardly be considered successful. In reality, his voyage, commissioned by the Dutch West India Company (WIC), continued to yield misery and disaster. Not surprisingly, the expedition never found the Unknown Southland; instead, after a terrible voyage involving the shipwreck of the *Afrikaansche Galey*, the mutiny of five disappointed sailors, the loss of a great many crew members due to malnutrition and diseases, the expedition reached the archipelago of the then Dutch Indies. Here, the two remaining vessels were seized by the authorities of the Dutch East India Company (VOC) on charges of ‘transgressing the limits’, meaning: illegal trading in VOC-territory. Fellow Dutchmen or not, the VOC took the matter seriously: Roggeveen and the other captains had to hand in their logs and other documents, and the ships were confiscated and sold. After an enforced stay of several months in Batavia (present-day Jakarta), Roggeveen returned, a disillusioned man, to the Netherlands aboard a VOC ship. The fate of the seized official documents remains unclear. All we know is that they were sent to the VOC Chamber in Amsterdam with copies to Middelburg, but they were never published in the eighteenth century. It was not until 1836 that a transcript of Roggeveen’s journal—written by four different VOC clerks—was found by an archivist, Mr. Pieter Pous, in an unusual location in Middelburg. A copy of the journal of Cornelis Bouman, captain of the *Thienhoven,* showed up in 1905 in the legacy of the Rotterdam harbour baron Hudig, a distant descendant of the VOC captain who at the time took Bouman back to the Netherlands. The journal of Roelof Roosendaal, captain of the *Afrikaansche Galey,* was presumably lost when his ship sank. The log of Jan Koster, captain of the *Arend*, and that of his first mate Jacob van Groeneveld, which are explicitly mentioned in the documents of the WIC, have never surfaced.

Because no official travelogues were published in the eighteenth century, knowledge of the voyage was limited. Still, the expedition has been written about. In 1724 François Valentijn published *Oud en Nieuw Oost-Indiën* (Old and New East Indies), a detailed overview of the history of the VOC. Roggeveen’s journey is mentioned very briefly in this work numbering more than 5000 pages and five volumes, but there is no word about Easter Island. In the years immediately following the expedition, people had to satisfy their curiosity with oral accounts. Six years after the tragic expedition, a travel account was published by a young German crew member, Carl Friedrich Behrens. We now know that he was a prolific writer. In 1728 he produced an account in verse, which was only (re)discovered a decade ago by the Dutch historian Roelof van Gelder in the library of Regensburg University, and which is now available digitally (Van Gelder 2012). In the title, we read: *In einem Send-Schreiben an einem guten Freund mit Poetischer Feder entworffen* (designed in a missive sent to a good friend with a poetic pen), so we do not know how widely it was distributed and read at the time, if at all. In 1732 Behrens wrote, probably on commission, another report entitled: *Nader onderzoek door Karel Fredrik Behrens:*

En bericht van zyne reyze naar de Zuid-Landen gedaan (Closer Examination by Karel Fredrik Behrens: An Account of His Voyage to the South Lands). It is a slender volume addressed to the VOC, published in Dutch and never translated, arguing in favour of continuing the quest for the 'great southern continent'. In 1737 Behrens published a 'full story' of his voyage, in prose, and printed in Frankfurt. Two years later, it received a second impression with a slightly different content and title. This is the well-known *Der wohlversuchte Süd-Lände*r (On the Well-Sought for South Lands), published in Leipzig (1739), widely read and soon translated into French (1739), Dutch (1759), and finally in English (1903). A sloppily edited version in German was published by Dr. Hans Plischke in 1923; it received a second print in 1925.

The only accounts of Roggeveen's expedition that were published by Dutch authors shortly afterwards and mentioned Easter Island were two short narratives. One of them, the *Tweejaarige Reyze* (A two-year voyage, Anonymous 1728), was written by an anonymous crew member aboard *De Aren*d; the other carries the initials 'T.D.H.' and was based on information received from a sailor who had been a crew member on board the *Afrikaansche Galey*. T.D.H. is probably a Mr. De Haze who is named in an epilogue at the end of the account by a certain Werner Köhne (W.K.). The story written by T.D.H. was reprinted four times, with different publishers, and sometimes with substantial changes in the content and the title (1727a, 1727b, 1727c and 1727d), probably as a result of 'predatory printing'.[2] The first printed edition (1727a) even lacks the initials of an author, but the title and content make it clear that it originates from the same person as the other three published that same year. In this chapter, I have used the last edition, an impression, according to the title page, 'revised anew by an eyewitness of this voyage, and augmented with necessary annotations'. The *Tweejaarige Reyze* was reprinted twice, almost unchanged, in 1758 and 1764.

Both stories were retold, almost verbatim, but abridged, in a collection of Dutch travel accounts (*Nederlandsche Reizen*, Vol. 13, 1787). All these Dutch eighteenth-century publications managed to reach many readers during their printing period, but so far both publications have hardly received any attention in the scholarly literature.[3] This is most likely because they were considered less informative and highly unreliable. Consequently, they have never been translated. This chapter aims to explain a special piece of 'fake news' that appears in both accounts: the existence of human giants on Easter Island. Why was it believed back then (if it really was), and what can we learn from the proposed explanation for our current struggle with questionable or downright false information? Why are certain myths so persistent? I begin with two excerpts from the previously mentioned accounts pertaining to Easter Island.[4]

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[2] Predatory printing was a common practice to avoid paying dues to publishers and/or writers.

[3] A project to publish all these Dutch eighteenth-century publications in one annotated volume is in progress.

[4] I would like to thank Rolf H. Bremmer Jr. for translating these excerpts.

2 Excerpts from Two Accounts[5]

From: T.D.H. (1727d)
(p. 9) ‘On the 6th [of April JJB], they sighted an island hitherto unknown to Europeans at 27 degrees South Latitude and 26 8 degrees of longitude. Since it happened to be Easter that day, they called it Easter Island. Here they met a small vessel patched together with chips as big as a hand, in which was a human, brown of countenance, whom they caught but also released, since they could not understand him. On the 8th they saw many inhabitants of the island swimming in the sea, and this in such a multitude that no one of the crew dared go ashore. But these people climbed on board, and marvelled about everything, especially the guns, and seemed inclined to stealing and robbing,[6] and did not leave the ship until they were expelled with force When our voyagers undertook a landing on the 10th of this month, they perceived a countless multitude on the beach, who tried to prevent them from landing. But they were quickly chased off and all took to their heels, as soon as some of them felt the power of the flintlocks and were injured by the bullets; . . .

(p. 10) . . . their corpses were carried away by the fugitives. Nevertheless, it taught them politeness, and they brought all kinds of fruits, sugar, *rottingen* [sugarcane? rattan?], *janbesambes* [bananas] and a great abundance of fowl. Their clothes were of many colours and a mixture of cotton and silk. Their ears hung down to their shoulders, and provided with many and such big holes that it was possible to put through a fist. The men[7] were twelve feet tall, so that a European could easily pass between their legs, and were also strong of body. But the women were about ten to eleven feet tall. The men’s faces and bodies were painted red or brown and those of the women purple.[8] Their idols were two stones of a special size, . . .

(p. 11) . . . which they worshipped. The broader stone was on the grounds. On it was placed the other one of such a size that seven men could hardly encircle them, so that it seemed impossible that, these stones could have been moved or placed on top of each other by the inhabitants, however tall and strong they might be. For

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[5] Footnotes 7–10 are by the author of the excerpt.

[6] Indeed, almost everyone who has traversed the South-Sea has confirmed that the inhabitants of these areas have glue on their hands and predatory claws.

[7] Many testimonies are found with authors about the exceeding and sturdy size of the people inhabiting the regions stretching towards the South Pole. I would not dare to swear on the description, according to which these people are ascribed such sizes, because I fear that the measuring has not been carried out mathematically but ‘guessimathically’. It can rightly be said: If you are told something big, from distant lands. It grows on the tongue, becomes stranger in the hands. Of writers of travelogues, who lard their work with rare accounts. And make it sweeter in their recounts. A hill is a mountain, a mountain splits the clouds. The shallows, though not deep, are bottomless swirls. A giant is oft made out of a full-grown man, *Because he pleases best, who can best exaggerate.*

[8] But since various authors write that these people of this climate are born brown- and copper-red, it can reasonably be doubted whether this red colour is congenital in the inhabitants of this island.

it was about the height of three men. Near the top of that rock a human head had been carved, adorned with a crown, made up of trim and inlaid with black and white squares. The name of the largest idol was Taurico, and that of the other Dago.[9] For with these words they called to their imagined gods, which they did with dancing, cheering, going round in circles, even with clapping their hands in almost the same manner as the children of Israel did when they sinned in serving the golden calf. When these islanders heard fire a heavy shot, ...

(p. 12) ... they behaved very strangely, and after many grimaces, these pointed with their fingers now to our crew now to their imagined god whom they at the same time implored for help, shouting with a loud voice, Dago! Dago!

Meanwhile, a clear wind started to gather and all three ships had almost stranded, and the Dutch would have been deprived of them. Therefore, they set sail again on the 12th of April, on a westerly course'.

From: Anonymous, *Tweejaarige Reyze* (1728)

(p.41) 'On the 6th of the same month, we discovered an island at 27 degrees south latitude and 26 8 degrees longitude, which had hitherto been unknown and undiscovered by any European; which is why we, according to the custom that newly discovered islands are given a name, called it Easter Island, because we had arrived precisely on the day on which the memory of the resurrection of Our Lord is celebrated. As soon as the anchors had been dropped, we perceived a strange little boat of a very ingenious shape, completely patched together from pieces of wood, hardly the size of half a foot. This little boat was steered by a single man, a giant of twelve feet tall, who vainly ...

(p. 42) ... did his utmost to escape from us, because he was surrounded and caught. His body was painted with a dark-brown colour. With signs and words that are spoken here and there in the South Sea, we tried to get some information from him, but could not notice that he understood anything, so that we placed him in his little boat again and allowed him to go.

Two days afterwards the sea was covered with the savage inhabitants of this island, who swam and swarmed in such a multitude around our ship that we neither could nor thought advisable to sail to land. They clambered like cats with extreme boldness up the sides of the ships, and got on board, since they did not seem to have the least fear of us. But they showed great marvel at the size and vastness of our ships, with all the trimmings and did not know what it meant. But their curiosity was directed especially towards the naval cannon, of which they never got tired to watch, and on which they often laid their hands in order to try to lift them and take

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[9] It would be odd if no one of the readers of this history would come to think whether this huge and Dagon worshipping multitude were issue of the Canaanites, who amongst others served Dagon (compare Judges 16: 23–24 with 1 Sam. 5: 3–6) and who were of a very exceeding length, but expelled by Joshua. But it is more credible that these people had unintentionally arrived from the continent on these islands, or had possibly been expelled. For many and most eyewitnesses ascribe the Patagonians and inhabitants of the Magellan shores a length of twelve feet or more. But that these Phenicians and tall people would be descendants of the aforementioned expelled peoples and have traversed the Ocean to these islands, is a claim that no one can bravely maintain or deny.

with them; but when they saw that such blocks could not be moved by many of them, however tough of muscles they were, these sturdy blokes were standing very timidly, and, it seemed to us, quite unsettled.

No matter how quickly they had come into the ships, we immediately experienced that by nature they were so thievish and quick of hand as the people that inhabit the islands, which voyagers call the islands of thieves, on account of the great pleasure which the inhabitants take in stealing and robbing. Rusted nails, scrap iron, and anything they could take and seize after their liking, with which they swiftly jumped overboard. They thought it was possible for them to scratch the bolts from the ship with their fingernails, but they were fixed too firmly. These tall blokes at last came in such number into the ships, that we only with great difficulty managed to keep order and watch their movements and fast hands; so, fearing they could become too strong for us, ...

(p. 43) ... we did our best to make them leave and remove them with kindness from the ships; but they did not seem to be able to make that decision, so that we were forced to employ heavier measures and chased these savages away with force off the ship.

The 10th of April we sailed well-armed with the sloops to the island so as to make a landing and inspect this province, where an innumerable crowd of savages was waiting on the shore to defend the beach, and to prevent us from landing. They threatened us immensely with their gestures, and showed to have all good courage to wait for us, and turn us away from their land, but as soon as we (compelled to do so) discharged a volley from our flintlocks on their coarse skin, so that here and there some fell with their noses in the sand, they lost courage. They made the strangest gestures and movements in the world, and looked with the highest surprise at their fallen comrades, and the wounds made by the bullets in their bodies, upon which they quickly took to flight with scary howls, and dragged all the bodies of the fallen with them and went land inwards, so that we had cleared the beach and landed safely.

These peoples do not go about naked, like many other savages, but they all wear clothes, which are curiously sewed or woven together from silk and cotton in various colours. But nothing is more unbecoming than their ears, which are awfully long, and hang down to the shoulders of most of them, which, although they consider this the greatest adornment, made them look to us, who are not accustomed to them, very awful; the more so, because they had such excessively large openings and holes in them, that we could easily put our hands through them.

So far, my narrative will have received some credibility, because it does not in itself concern anything extraordinary; however, I must say that these savages are of a more than gigantic stature. For the men, who are at least twice as tall as one of the sturdiest men aboard the ships, stretched on average to about twelve feet, ...

(p. 44) ... so that we easily (who would not be surprised?) without bending our heads would have passed between the legs of these children of Goliath. In proportion to their length is their width, and all their body parts are on average shapely formed, so that each of them could have passed for a Hercules. But none of their women matched the men in length, and do not usually stretch to more than ten or eleven feet. These men had their bodies painted with a red or dark-brown colour, and the women with a scarlet one.

I do not doubt, or most people who will read this travelogue will not give me credibility and easily take this account of the length of these giants for merely a fable or a figment. But this I assure that I have full consciously written down nothing against the truth, and that this people, viewed with a careful eye, are indeed so exceedingly tall, as I have described them here. Agreeing with me in this point are all famous voyagers, who have ever sailed these seas, men of good faith, whose narratives cannot be mistrusted, without doing them wrong. They concur unanimously in their travelogues that giants are being found in the lands on and in the South Sea, of a size far exceeding ours, and well in agreement with that of our islanders, as we will demonstrate in more detail in the next chapter'.

3 Analysis of the Content

The short narratives have many similarities but also a few striking differences. To begin with the similarities: in both we read about the naming of the island, about the first encounter with an islander and the many inhabitants who climbed on board in the following days and grabbed some loose stuff they could lay hands on and take home. The description of the clothing as consisting of cotton and silk and the painting of the skin also matches, while the pierced and stretched ear lobes appear impressive. The shooting incident is mentioned and for justification both authors argue that the islanders would have made the landing difficult. The carrying of the dead is noticed by both. The stories are also strikingly unanimous on the islanders' gigantic stature. The alleged height of the men (12 feet) and the women (10–11 feet) is identical, including the statement that the European visitors could easily walk between their legs.

Because of the many similarities, sometimes in literally the same terms, the possibility arises that the stories stem from the same author. This conclusion is contrary to the information provided by the authors themselves in their reports. T.D.H. writes that he heard the story from a survivor of the 'Smallest Ship'. This was the *Afrikaansche Galey*. Of the one hundred and eleven crew members, only six survived, including the man 'to whom I owe this story'. The third impression, according to the title page, is 'revised anew by an eyewitness of this voyage'. The author of the *Tweejaarige Reyze* writes that he was a crew member on board the *Arend*. The similarities can most likely be explained by assuming that both stories may have been influenced by the many stories that circulated about the voyage in the years after the survivors had returned. It took five years for some of these oral accounts to be put on paper. Even the author who experienced the journey himself may not have limited himself to his own memories.

There are also some notable differences. For example T.D.H. lists a few products that the islanders offered to the Dutch after the shooting incident. Among them are two that are difficult to identify. He makes mention of *rottingen*, here translated as 'rattan', but which can also be an abbreviation of *rottingsuikerriet* (sugar cane stalks), and about *janbesambes*, probably (sweet) potatoes or another root vegetable.[10]

Furthermore, T.D.H. pays much attention to the *moai*, the large statues of Easter Island, which, curiously enough, are completely absent from the description of the *Tweejaarige Reyze*, even though the anonymous author of this document himself experienced the journey. T.D.H. describes two statues, both their base (the *ahu*) and their headgear (the *pukao*). He also mentions the names by which they are called: *Taurico* and *Dago*, names that are attested nowhere else in eighteenth-century Easter Island accounts. He thinks the statues are idols because the islanders' behaviours—dancing, clapping, and shouting—reminds him of the way in which the Israelites, according to the biblical book of Exodus, worshipped the golden calf in the desert. The comparison reveals the author's mindset and his time.

Aside from inaccuracies in observation (cotton or silk clothing), interpretation (impediment to landing) or in listening (names of statues), the most remarkable thing is that these accounts tell us that there are giants on Easter Island. They report men and women up to ten or twelve feet tall. The travel reports of Roggeveen, Bouman, and Behrens are silent on this point. From what we know of the osteological records, the report is totally beyond reality, not only with respect to Easter Island, but everywhere in the region or on earth. How should this eighteenth-century 'fake news' then be explained?

4 Explanatory Framework

To this end, the theoretical work of British environmental scientist Mike Hulme and the empirical studies of Yale psychologist Dan Kahan may be helpful (Hulme, 2009; Kahan 2010, 2012, Kahan et al. 2011). They independently investigated the effect of (science) communication. Why do people arrive at different evaluations based on the same data? Why is certain information considered to be reliable? In his book *Why We Disagree about Climate Change,* Hulme points out the importance of the underlying philosophy of life, the way people give meaning to their lives. This world view forms, as it were, a substrate for the interpretation of reality. We must not only talk about the facts, thus Hulme, but also try to probe and address this deeper and tougher layer. In his view, climate change is also a cultural problem, which has consequences for communication. Piling fact upon fact or 'explaining the matter well again' will not help in the short term to change someone's mind if there are fundamentally conflicting world views. In one of his empirical studies, Kahan and his collaborators described how the interaction between facts and this substrate can work. They had ideologically mixed groups judge book proposals by three (fictional) male scientists (Kahan et al. 2011). Business information about this trio

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[10] Prof. Nicoline van der Sijs, personal communication, January 2021.

was provided. They were scientists with resounding bios, including a membership of the National Science Academy (NAS) in the USA and solid scientific reputations. The intended books would address major societal questions in their own field: nuclear energy, climate change, and gun possession, respectively. The subjects had to assess the author's expertise and reliability on the basis of a substantive abstract of each book. They were not asked for an opinion on the actual content and tenor of the proposal. What they did not know was that two versions were put into circulation that contrasted strongly with each other. For example there was an abstract in which climate change was characterized as a major risk that necessitated action and also one in which many of the presumed dangers were called 'premature'. In short: there was a fairly progressive, alarming version and a conservative version. What turned out? The stronger the agreement between the subjects' own views and the proposal concerned, the more expert and reliable the author was found. There is apparently a cultural bias in the way people judge apparently factual information, Kahan says. Their own basic attitude tainted the perceptions of the information giver and distorted the perception, sometimes unconsciously. And this bias can be significant.

5 Application to the Case

Hulme and Kahan both point out the importance of an underlying world view, the role of experts who inform us—whether they are considered to be reliable or not—and the (biased) perception. Precisely these three ingredients play a role in the 'observation' of giants on Easter Island. This becomes clear when we compare the two stories on this point. There is no difference in the details with which the huge people of the island are described (10–12 feet in length, walking between the legs). Both authors also refer to 'testimonies' of 'experts', in this case travellers who have visited these regions before and also reported the presence of giants. However, T.D.H. questions the expertise of all these witnesses in a footnote. He wonders whether the correct method was used for determining the length. Was it mathematically or 'guessimathically' (translation of the Dutch pun 'wis-konst' or 'gis-konst'), he asks rhetorically? In his own worldview, such problems are apparently to be solved with the help of measurements, science. The author of the *Tweejaarige Reyze* can well imagine that the readers are questioning his statements about giants, but he nonetheless relies on the expertise of previous travellers. These were unanimous in their testimony to the presence of giants elsewhere in those southern regions. And they were 'men of good faith', you just cannot dismiss their accounts. The author feels the need to justify his opinion in a separate chapter. The title of this chapter already brings out from which ideological source he is drawing[11]: the Bible. His way of arguing is clear enough. In the biblical stories, we come across giants. They existed, according to the book of Genesis, in primeval times (Gen. 6: 1–10) and also in the land of Canaan. When the twelve spies explored this land, they saw not only very tall men, such as Goliath, but also taller ones, called 'sons of Enak'—giants, in whose eyes they looked like grasshoppers (Numbers 13:32, 33). But once the people of Israel have conquered the land, these giants disappear from the biblical stories. Where did they go? In the Christian West, where the Bible was an authoritative book, a widespread belief prevailed that these giants had moved to the 'edges of the earth'. When the great European voyages of discovery began in the sixteenth century, it was hoped that they would still be found somewhere. Such a (re) discovery would, of course, give the finder tremendous status and once again underscore the reliability of the Bible.

And sure enough … the giants appear. Magellan saw them on his world tour in Patagonia, the extreme southern point of Latin America. The chronicler of this voyage, Pigafetta, describes the find in 1519 and the region is marked *Regio Gigantes* (region of the giants) on maps (Pigafetta 1874).[12] A century later, the Dutch captains Schouten and Lemaire also arrive on their journey around the world (1615–1617) in this region and confirm the presence of the giants in their travelogue. Although they did not see them in person, they did find graves with gigantic bones. These graves and the bones are recognizable on an engraving in Schouten's journal (Schouten 1945).[13] According to the caption, the skulls were so big they could be put over one's head like a helmet. Other witnesses follow. English travelogues show pictures of European sailors next to giants, which are almost twice as long.

Two centuries later, when Roggeveen set sail in search of the unknown Southland, the *Regio Gigantes* is still indicated on maps of Patagonia. Although fewer and fewer travel reports mention their existence, belief in their existence is far from gone. The giants might still be there, somewhere down under. And why not on islands in the Pacific? This is the mindset of the writer of the *Tweejaarige Reyze,* and we recognize in his 'proof' the three characteristics of Hulme and Kahan. There is a philosophy of life, and there are witnesses who have seen things that fit this philosophy and thereby confirm it. But while in Magellan's time the Bible was still very generally used in Europe as an ideological basis for the view of reality, this was less so in Roggeveen's time. The Reformation had paved the way for an independent role for 'the book of nature' as a second source (apart from the Bible) to obtain reliable knowledge of God and His creation (Harrison, 2001). Scientific methods proved most suitable for the study of the book of nature, especially mathematics, according to Galen. In the worldview of T.D.H. natural science had also acquired a place as a frame of reference in addition to, or perhaps even instead of the Bible. Perhaps he had also started to read some parts of the Bible differently, less

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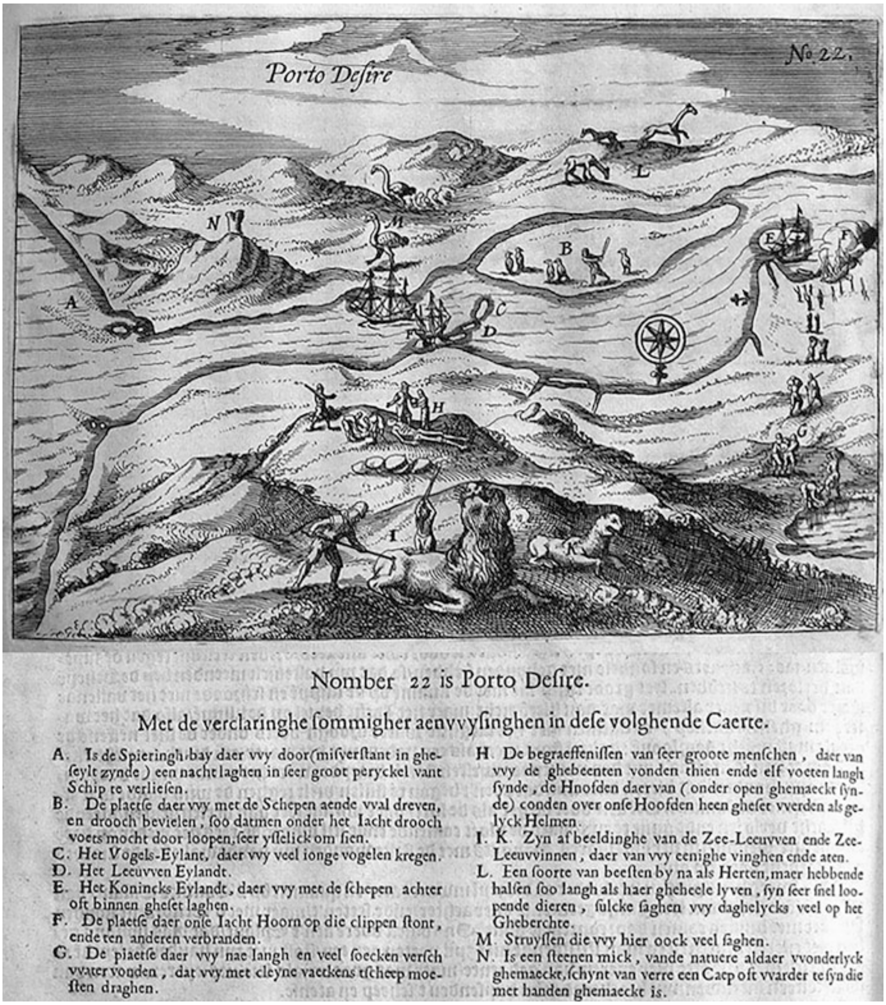
[11] First sentence of the title: 'Dat'er Reuzen zyn word bewezen uyt de H. Schriftuur en de beste Reyzigers' (The existence of giants is proved by the Holy Scriptures and the best travellers).

[12] 'He was so tall that the tallest of us only came up to his waist', Pigafetta (1874, 50).

[13] The name of the engraving is *Caerte van Porto Desire*. In: Schouten (1945, 162).



Nomber 22 is Porto Deſire.

Met de verclaringhe ſommigher aenvvyſinghen in deſe volghende Caerte.

A. Is de Spieringh-bay daer vvy door (miſverſtant in gheſeylt zynde) een nacht laghen in ſeer groot peryckel vant Schip te verlieſen.
B. De plaetſe daer vvy met de Schepen aende vval dreven, en drooch bevielen, ſoo datmen onder het Iacht drooch voets mocht door loopen, ſeer yſſelick om ſien.
C. Het Vogels-Eylant, daer vvy veel ionge vogelen kregen.
D. Het Leeuvven Eylandt.
E. Het Konincks Eylandt, daer vvy met de ſchepen achter oft binnen gheſet laghen.
F. De plaetſe daer onſe Iacht Hoorn op die clippen ſtont, ende ten anderen verbranden.
G. De plaetſe daer vvy nae langh en veel ſoecken verſch vvater vonden, dat vvy met cleyne vaetkens tſcheep moeſten draghen.
H. De begraeffeniſſen van ſeer groote menſchen, daer van vvy de ghebeenten vonden thien ende elf voeten langh ſynde, de Hnofden daer van (onder open ghemaeckt ſynde) conden over onſe Hoofden heen gheſet vverden als gelyck Helmen.
I. K. Zyn afbeeldinghe van de Zee-Leeuvven ende Zee-Leeuvvinnen, daer van vvy eenighe vinghen ende aten.
L. Een ſoorte van beeſten by na als Herten, maer hebbende halſen ſoo langh als haer gheheele lyven, ſyn ſeer ſnel loopende dieren, ſulcke ſaghen vvy daghelycks veel op het Gheberchte.
M. Struyſſen die vvy hier oock veel ſaghen.
N. Is een ſteenen mick, vande natuere aldaer vvonderlyck ghemaeckt, ſchynt van verre een Caep oft vvarder te ſyn die met handen ghemaeckt is.

Caerte van Porto Desire, after Schouten 1945, 162

literally and hence changed his ideological base. This might explain the difference in interpretation and weighting of the ‘facts’. T.D.H. is careful and clearly does not want to sneer at his informant. He simply writes down in the main text what he has heard, but asks questions about the method in a footnote and adds a rhyme to render implicitly his own explanation: exaggeration to please the readers.

6 Outside of Reality?

Although it may be clear from the above why in the travel stories the stated height of the residents has taken on giant dimensions, towards fable or, as we are now inclined to say, ‘fake news’, the question remains whether there was any reason for this claim in reality. Would there have been anything on display in Latin America or Easter Island that justified or evoked the exaggeration? This turns out to be the case. Relevant indications can be found in the literature on both regions. The first concerns South America and comes from none other than Charles Darwin. On his famous voyage with the Beagle (1831–1836), he also passed through the Strait of Magellan and described the inhabitants of Patagonia as follows: ‘on an average, their height is about six feet, with some men taller and only a few shorter; and the women are also tall; altogether they are certainly the tallest race which we anywhere saw’ (Darwin 1910, 229).

The second clue comes from the journal of a Spanish expedition to Easter Island in 1770. The Spaniards saw a lot of tall men on the island. Gonzalez, the expedition leader, writes that most men are taller than 8.5 Castilian *palmos*. Out of curiosity and entirely in line with the enlightened *zeitgeist*, they measured two men precisely. The tallest male turned out to be 9 *palmos* and 3.5 *pulgadas*, while the other one measured 9 *palmos* and 2 *pulgadas*, which equates to 1.97 and 1.94 metres, respectively. Two ‘giants’, certainly compared to the visitors from Southern Europe, who at the time had an average height of around 1.6 metres (about 5 cm less than in Northern Europe, Steckel 2001). Tall people existed in both Patagonia and Easter Island, so tall that there was evidently a great temptation to see descendants of the ‘lost’ Biblical giants in them.

To summarize: people are not blank observers, they look, sometimes unconsciously, at reality from certain ideological perspectives. If they then see or hear something that seems to fit and confirm their philosophy of life, it receives selective attention. The tendency to then exaggerate the evidence is considerable and, depending on the context, may sometimes assume fabulous forms and so become ‘fake news’.

7 Relevance for our Present-Day Debate

The above analysis of the eighteenth-century report about giants also seems to me relevant for interpreting the discussions conducted held today about the history of Easter Island. To exemplify this assumption, I take the ‘collapse theory’, in the version that has gained worldwide fame through the work of Clive Ponting and in particular the mega bestseller of Jared Diamond (Ponting 1991; Diamond 2005). The core of this theory is the assertion that Easter Island experienced a complete collapse of island culture as a result of the over-exploitation of natural resources, a few decades before the arrival of Dutch visitors. Deforestation is said to have washed away fertile soil, causing hunger, war, cannibalism, and mass mortality. The first visitors would have found the meagre remains of a once thriving culture. Initial support for this theory has all but disappeared among Easter Island researchers. I refer to my previous publications for a thorough substantive treatment and refutation of the theory (Boersema 2002, 2011, 2015, 2015a, 2017, 2020; Boersema and Huele 2019). Here, in this chapter, the important question is in what context the theory originated and why it remains so popular in certain circles, even though it has long been proved untenable.

For the 'collapse theory' to emerge, we have to return to the beginning of the environmental crisis in the 1960s. Partly because of the work of Rachel Carson, people began to worry about the negative effects of industrial development and the growing use of toxic substances. The realization dawned that there was more to it. Alarming studies pointed to disappearing nature, diminishing resources and an exponentially growing world population (one among many: Paul R. Ehrlich 1968). It may be that in all this the New Testament stories about an apocalypse resonated, whether or not in a secular Malthusian version.[14]

The publication that made the most impression was the Report to the Club of Rome of 1972 (Meadows et al. 1972). This report described an advanced world model for the time that simulated what would be in wait for us, if policy remained unchanged. The graphs produced by the computer at MIT in Cambridge, MA, were unsettling. The over-exploitation of natural resources would lead to depletion and reduce carrying capacity. The population size would decline dramatically. Without measures, we faced a social disaster in the middle of the twenty-first century, a real collapse. The launch of the report caused a shock. It created a new state of mind on how to evaluate the state of the planet. Scientists, and in their wake worried citizens, wondered what to expect. The causal mechanisms behind the model seemed plausible, but they remained theoretical. Could the past lend some support? Perhaps mankind had experienced something similar on a smaller scale previously in history? This question also puzzled the American archaeologist William (Bill) Mulloy. Mulloy was a member of Thor Heyerdahl's Easter Island expedition in the 1950s and later returned to the island, including for the restoration of the Tahai complex. Mulloy studied not only the turbulent history of Easter Island but also the environmental literature. The latter changed the way he viewed the world. He was impressed by the gloomy studies and wondered: 'could something have happened on Easter Island'?[15] His pessimistic worldview made him sensitive to reinterpret and combine certain phenomena in the past. Since the island's history was full of unsolved riddles, it left room for diverging, even speculative, scenarios. This might explain why the serious and well-respected scientist he was, Mulloy published a popular article describing a 'Club of Rome-esque' scenario, including a full-scale civil war and mass starvation, which would have taken place in the late seventeenth

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[14] This has also been suggested for Easter Island. See: Ingersoll and Ingersoll (2013, 47–52).

[15] Interview with his daughter, Briged Mulloy, July 2012.

century. A real pre-European collapse (Mulloy 1974).[16] It was a pretty wild story, the evidence was paper thin, but it marked the birth of the collapse theory for Easter Island. Mulloy had been handed collapse spectacles that matched his own deeply felt worries about the ongoing environmental degradation. He looked through these spectacles at the past and thought he saw confirmation of it. Subsequently, the Easter Island collapse story began a ramble in which it successively ran into the deep-sea diver Jean Y. Cousteau, the Dutch Committee for Long Term Environmental Policy CLTM, Clive Ponting and, finally, Jared Diamond (Cousteau 1983; CLTM 1990; Ponting 1991; Diamond 2005). It is unclear whether they were aware of each other's publications, for none of them mentions a predecessor. Today, the theory is mainly linked to Jared Diamond, as the most famous scientist on the list. In this short description, I am not concerned here with assessing the evidence, but above all with the demonstrable link between the deeper-lying belief that 'the earth is not doing well' and the perception of reality that is influenced by it, in this case the historical reality.

The same link plays a role in the continued popularity of the Easter Island collapse theory. A striking example is presented in a statement by the economist and Nobel Prize winner Joseph Stiglitz. Like many responsible citizens of the world, he is deeply concerned about climate change and the role of humans in it. Over-exploitation, inherent to capitalism is to blame, according to Stiglitz, who continues: 'it reminds one of Jared Diamond's story of collapse on Easter Island where they cut down the last tree and they were unable to paddle to any other island and they'd destroyed their future'.[17] Stiglitz is an exceptionally good economist, but there is no evidence that he has studied the recent literature on Easter Island. He is sensitive to the idea that a collapse in the nearby future is possible, presumably because he shares Diamond's and others' pessimistic world view. Additionally, Diamond, being an Ivy league scientist, is considered a reliable witness. In the words of the writer of the *Tweejaarige Reyze*: 'a man of good faith'. Stiglitz takes the Easter Island story to illustrate and underline his own deeply felt concerns and economic advocacy for change without checking Diamond or the facts.

A second example—underscoring the importance of the link—comes from my own experience. In 2019 the Dutch journalist and historian Rutger Bregman published a book with the telling title *De meeste mensen deugen. Een nieuwe geschiedenis van de mens* ('Most people are good. A new history of humankind' translation JJB). It became a tremendously successful book and has sold well over a two hundred thousand copies in the Netherlands. Translations into English and German followed suit and also became bestsellers (Bregman 2019, 2020). In his book, Bregman has analysed and summarized a large number of studies that show that people are more likely to commit themselves to others and to the common

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[16] It includes a pre-quote from Ehrlich's book stating that 'The battle to feed the world is over. In the 1970s and 1980s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now' (Paul R. Ehrlich 1968, xi).

[17] *The Guardian*, 4 November 2018.

cause than to self-interest. Altruism is not a thin veneer. Some of the studies were well known but misread for a long time. For sure, a remarkable collection. The book is written from an optimistic view on humankind, and the selected studies seem to support but also justify this message. Bregman himself speaks of a realistic view on human nature. My interpretation of Easter Island's ecological history (no collapse, but adaptation and resilience) is one of the studies that were included in Bregman's book. It became the core of Chap. 6. I was honoured and gained a new audience. From then on, I have found myself often in 'one of two worlds', when I lectured about my Easter Island research. In these lectures, I tried to stay as close as possible to my reconstruction of the past. The tenor was always: there is no evidence of a collapse, the population showed resilience. It remains to be seen if 'Earth Island' equals Easter Island (Bahn and Flenley, 1992). Before the publication of Bregman's book, when my audience consisted mainly of environmentally minded people, I often received very critical questions and many in the room were not inclined to give up the idea of a collapse. Apparently, it was thought that a (less) dramatic reading of the history of Easter Island would have implications for the assessment of the current environmental crisis. This was also explicitly stated: 'We need such a story, don't we, Jan'? During lectures to an audience of Bregman readers, I was asked the opposite question: whether I saw no support in the events on Easter Island for an optimistic view of the crisis today. People liked to see that hopeful view nurtured and confirmed by the history of this remote 'model island'.

In these examples, we recognize the triad of Hulme and Kahan: a pre-existing philosophy of life, expert witnesses, and the selection and interpretation of the facts. Their work has proved helpful in understanding apparent incongruities. It also points to a possible solution: involve the underlying world view in the analysis.

Accounts of the Expedition of Jacob Roggeveen 1721–1722

Anoniem (1728) *Tweejaarige Reyze Rondom de Wereld, Ter nader Ontdekkinge der Onbekende Zuydlanden. Met drie schepen, in het Jaar 1721, ondernomen, door last van de Nederlandsche Westindische Maatschappy, Waar in het wedervaaren en de Rampen op de Reyze verhaald, en de bezeylde en nieuw ontdekte Landen en Eylanden, met der zelver Bewoonders, beschreven worden. Nevens de Reyze van het Oostindisch schip BARNEVELD, Uyt Holland tot aan de Kaap der Goede Hoope, in 't jaar 1719. Behelzende Een verhaal van de langduurige tegenspoeden en zonderlinge voorvallen op het Eyland Madagascar, by de Woeste Souklaven. Met een naauwkeurige Beschrijving van de vreemde Gewoontens, Godsdienst en Zeden dier Volkeren. Verciert met een Nette Reyskaart en Prentverbeeldingen.* Te Dordrecht, Gedrukt by Joannes van Braam, boekverkooper, 1728.

(Anonymous (1728) A two-year voyage around the world, For a Further Discovery of the Unknown SOUTHLANDS. With three ships, in the year 1711, undertaken at the order of the Dutch West Indies Company, In which the experiences and disasters are related, and the sailed and newly discovered lands and islands, with their inhabitants are described. Together with a voyage of the East Indies ship Barneveld, from Holland until the Cape of Good Hoop, in the year 1719, Concerning A Story of the long-lasting misfortunes and strange events on the island of Madagascar, with the savage Souclaves, with an accurate description of the strange customs, religion and mores of these peoples, adorned with a precise itinerary map and pictures Dordrecht. Printed by Jannes van Braam, Bookseller, 1728.)

Other editions: Van Braam, Dordrecht (1758), H. De Koning, Dordrecht (1764), and retold in *Nederlandsche reizen,* Volume 13 (1787), Petrus Conradi, Amsterdam/V. van der Plaats, Harlingen.

Behrens, Carl Friedrich (1728) *Reise nach den unbekandten Süd-Ländern und rund um die Welt / Nebst vielen von ihm angemerckten Seltenheiten und zugestoßenen wunderlichen Begebenheiten. Unbey eine wahrhaffte Nachricht von der Insul und Historie des Robinson Crusoe. In einem Send-Schreiben an einem guten Freund mit Poetischer Feder entworffen.* Frankfurt und Leipzig.

(1732) *Nader onderzoek door Karel Fredrik Behrens. En bericht van zyne reyze naar de Zuid-Landen gedaan, in dienst van de E: WEST-INDISCHE, COMPAGNIE, in den Jare 1721 enz. Thans volgens eigen ondervinding, ten beste opgedragen aan de E: OOST-INDISCHE COMPAGNIE van Hollandt.* t'Amsterdam, gedrukt voor den Autheur.

(1737) *Karl Friderich Behrens selbst gethane Reise und Begebenheiten durch die bekannte und unbekannte Südländer und um die Welt. Worinnen Die die Canarische und Saltz-Insulen, Brasilien, die Magellanische und Lameerische Strassen, Küste von Chili, die neu-entdeckte Insulen, gegen Süden und unterschiedene Plätze in Asia, Africa und America; Wie auch deren Einwohner, Lebens-Art, Policey, Commercien, Gottesdienst und dergleichen beschrieben werden.* Gedr. Bey Joachim von Lahnen, Frankfurth.

A second print (1739) *Der wohlversuchte Süd-Länder, das ist: ausführliche Reise-Beschreibung um die Welt, Worinnen von denen Kanarischen und Saltz-Insuln, Brasilien, der StraβMagellanus und Lamer-Küste, Chili, und neu-entdeckten Insuln gegen Süden, ic. Deβgleichen von den Moluckischen Insuln und verschiedenen Plätzen in Asia und Africa, als auch ihren Inwohnern, Lebens-Art, Policey, Handel Wandel und Gottesdienst gehandelt wird. Nebst einer accuraten Charte der ganβen Welt, und andern Kupffern entworffen von Carl Friederich Behrens.* Auf Kosten des Autoris, zu finden bey Joh. Georg Monath, Leipzig.

Translation in French (1739) *Histoire de l'Expédition des Trois Vaisseaux, Envoyés par la Compagnie des Indes Occidentales des Provinces-Unies, aux Terres Australes en MDCCXXI.* Par Monsieur de B. 2 tom. Aux dépens de la Compagnie. La Haye. Vertaling in het Nederduitsch, Amsterdam (1759) en Engels (1903) Hakluyt Society, London.

Behrens, Carl Friedrich (1923) *Der Wohlversuchte Südlände. Reise um der Welt 1721/22* Nach den Originalausgaben bearbeitet von Dr. Hans Plischke, F.A. Brockhaus, Leipzig (2de druk 1925).

Mulert, F.E. baron (1911) *De reis van Mr. Jacob Roggeveen ter ontdekking van het Zuidland (1721–1722)* Verzameling van stukken, deze reis en de daaraan voorafgaande ontdekkingsplannen van Arend Roggeveen (1675–1676) betreffende. Werken uitgegeven door de Linschoten Vereeniging IV, Martinus Nijhoff, 's-Gravenhage. (Journal of Cornelis Bouman, pp. 178–205).

Mulert, F.E. baron (1911) *Scheepsjournaal, gehouden op het schip Tienhoven tijdens de ontdekkingsreis van Mr. Jacob Roggeveen, 1721–1722*. J.C. en W. Altorffer, Middelburg. Overgedrukt uit: Archief uitgegeven door het Zeeuwsch Genootschap der Wetenschappen, (1911), 62–180.

Nederlandsche reizen, tot bevordering van de koophandel, na de meest afgelegene gewesten des aardkloots. Doormengd met vreemde lotgevallen, en menigvuldige gevaaren, die de Nederlandsche reizigers hebben doorgestaan. (1784–87) Petrus Conradi, Amsterdam /V. van der Plaats, Harlingen (in Volume 13, 1787 the stories of the *Tweejaarige Reyze* and *T.D.H.* are retold).

Roggeveen, Jacob (1838) *Dagverhaal der ontdekkings-reis van Mr. Jacob Roggeveen met de schepen Den Arend, en De Afrikaansche Galei in de jaren 1721 en 1722*. Met toestemming van zijne excellentie den minister van koloniën uitgegeven door het Zeeuwsch genootschap der wetenschappen. De gebroeders Abrahams te Middelburg.

Anonymous (T.D.H.?) (1727a) *Kort en nauwkeurig verhaal, van de reize, Door drie schepen in 't Jaar 1721 gedaan, op ordre van de Ed. Heeren Bewindhebberen van de West-Indische Compagnie in Holland, om eenige tot nu toe onbekende Landen, omtrent de Zuid-Zee gelegen, op te zoeken*. (a 4 page pamphlet; no author, no publisher. Title identical to T.d.H.1727b, text shorter and slightly different).

T.D.H. (1727b) *Kort en nauwkeurig verhaal, van de reize, Door drie schepen in 't Jaar 1721 gedaan, op ordre van de Ed. Heeren Bewindhebberen van de West-Indische Compagnie in Holland, om eenige tot nu toe onbekende Landen, omtrent de Zuid-Zee gelegen, op te zoeken.* Te Amsterdam, bij weduwe Jacob van Egmont, boekdrukster en verkoopster op de Reguliersbreestraat in de nieuwe drukkerij.

T.D.H. (1727c) *Kort en nauwkeurig verhaal van de reize, door drie schepen in 't jaar 1721 gedaan, op ordre van de Ed. Heeren Bewindhebberen van de West-Indische Compagnie in Holland, om eenige tot nog toe onbekende landen, omtrent de Zuid-Zee geleegen, op te zoeken*. Te Amsterdam, by Johannes van Septeren, Boekverkoper op de Leydse straat, tusschen de Heere en Keysersgragt. (with the same Publisher in 1727 a second print).

T.D.H. (1727d) *Het Waare en Nauwkeurige Journael der Reize, gedaan door drie Schepen, op ordre van de Ed. Heeren Bewindhebberen van de West-Indische Compagnie, om eenige tot nog toe onbekende Landen, omtrent de Zuid-Zee geleegen, op te soeken. Waar in alles wat haar op de Reize is wedervaren, wert verhaalt en aangetoont; als ook de wonderlyke manieren, gewoontens, en zeden der ontdekte volkeren, en hoe deze Reizigers op eene wonderlyke wyze te Batavia zyn aangekomen* etc. Den Derden Druk, van veele Drukfeilen verbetert, op nieuws nagesien door een ooggetuyge van dese Reize, en met nodige Aantekeningen vermeerdert. Te Amsterdam, by Johannes van Septeren, Boekverkoper op de Leydse straat, tusschen de Heere en Keysersgragt.

(The True and Accurate Journal of the Voyage, made by three Ships, by order of the Hon. Directors of the West Indies Company, to search for some hitherto unknown Lands, situated nearby the South Sea, in the which everything that

they experienced during this voyage is related and shewn; as well as the strange manners, traditions and customs of the peoples discovered, and how the Voyagers arrived in a curious way at Batavia etc.

The Third Impression, with many printing errors purged, revised anew by an eye-witness of this voyage, and augmented with necessary Annotations. Amsterdam, Johannes van Septeren, bookseller, 1727).

Valentijn, François (1724) Oud en Nieuw Oost-Indiën, vervattende een Naaukeurige en Uitvoerige Verhandelinge van Nederlands Mogentheyd In die Gewesten. In vyf deelen Te Dordrecht by Joannes van Braam/te Amsterdam by Gerard onder de Linden. (volume 3 mentions Roggeveen's expedition).

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Part VII
Synthesis

Chapter 24
Towards a Holistic Approach to Easter Island's Prehistory

Valentí Rull and Christopher Stevenson

1 Introduction

As highlighted in the introduction, truly integrated interdisciplinary efforts to address the prehistory of Easter Island are conspicuous in their absence. Ideally, this type of initiative should be developed under the umbrella of a joint multidisciplinary project, but, in the absence of such a venture, a book like this could be useful in helping to set the foundation for a transdisciplinary understanding. To fulfill the main objective of the book, a final synthetic chapter that combines the information from the different disciplines included in previous chapters seems essential to examining the cultural journey of the Rapanui. In addition, it is hoped that this attempt could pave the way towards the development of joint multidisciplinary research projects.

This chapter is an attempt to combine some of the available archaeological, anthropological, paleoecological, and historical evidence into a holistic framework that considers the environment, the island landscape, and the living organisms it supports as a single integrated unit. One theoretical framework suitable for this task is human ecodynamics and niche construction.

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V. Rull, C. Stevenson (eds.), *The Prehistory of Rapa Nui (Easter Island)*,
Developments in Paleoenvironmental Research 22,
https://doi.org/10.1007/978-3-030-91127-0_24

2 Human Ecodynamics

2.1 *Theoretical Foundations*

The Human Ecodynamics (HE) theoretical framework was introduced by McGlade (1995), who defined this approach as the dynamics of human-modified landscapes under a long-term, nonlinear causality perspective. The concept involves the "co-evolution of socio-historical and natural processes, and their time-space intersection" (McGlade 1995; p. 126). Inherent to this model is that the idea of "environments" or "ecosystems" are not "single identifiable concepts independent of human observation" but "socio-cultural constructions embedded in contemporary attitudes and value systems" (McGlade 1995; p. 126). The focus of HE is coupled human–natural systems, also called socioecological systems or socioecosystems (Barton et al. 2004). HE involves the notion that humans should not be considered external to the environments in which they live, and have lived for millennia, but an integral part of them (Fitzhugh et al. 2019).

Concepts typical of human ecology such as stabilizing (negative) feedbacks, adaptation, equilibrium, stability, or predictability, have no place under the HE perspective, which is more compatible with ideas such as destabilizing (positive) feedbacks, self-organization, non-equilibrium, resilience, and unpredictability (chaos) (McGlade 1995). Therefore, HE may be viewed as the study of long-term millennial-scale ecological trends and processes (Rull 2020a). This involves the use of similar methods and approaches that incorporates a broader functional unit, the socioecological system, rather than solely the ecosystem. These methods include chronological inference, paleoecology and paleoclimate reconstruction, human paleodemography, migration mapping and dynamic socioecological modeling (Fitzhugh et al. 2019). This requires the integration of a number of disciplines such as geography, anthropology, environmental history and ecology (Kirch 2005). Due to their isolation, comparatively recent human occupation, and simpler socioecosystems, eastern Pacific islands such as Rapa Nui seem to be particularly well suited for integrative HE studies (Kirch 2007).

2.2 *The EHLFS Approach*

As noted above, HE shares methodological tools and approaches with a number of fields, especially with historical ecology. The EHLFS (Environmental-Human-Landscape Feedbacks and Synergies) approach (Rull 2018, 2020b) was first conceived within a paleoecological context but with human societies as an integral part of the socioecological system, as a functional unit. Actually, the EHLFS system may be considered a model representing the three main components, or subsystems, of the socioecosystem (i.e., the environment, the humans and the landscape) and their interactions (i.e., feedbacks and synergies) (Fig. 24.1). It thus provides a

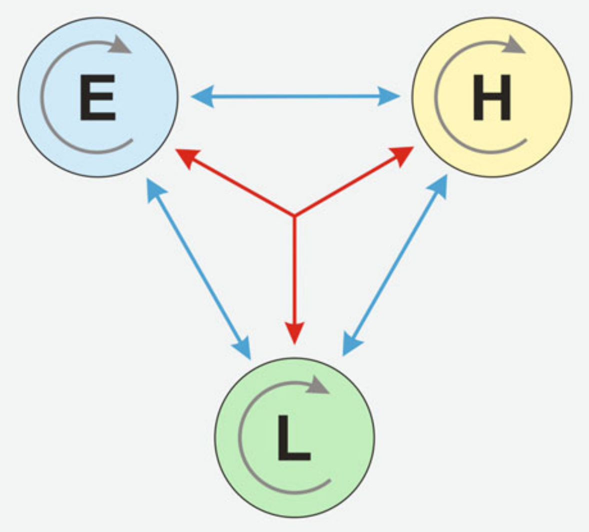

Fig. 24.1 Schematic view of the EHLFS holistic approach. E, Environment; H, Humans; L, Landscape. Feedbacks are represented by blue arrows and synergies by red arrows. Gray arrows represent internal subsystem feedbacks

comprehensive structure for the organization of system features and a way to track their interactions. Although not explicitly stated formerly, EHLFS is essentially a HE integrative approach that recognizes the uniqueness of human agency interfacing with other components of the system.

The three basic subsystems (E, H, and L) may include many elements, some of which are particularly relevant to define and characterize their interactions. Major environmental elements are climate change, geological patterns, or environmental hazards (volcanism and earthquakes), as well as all the associated astronomical, atmospheric, oceanic, and lithospheric drivers and processes. The human component is represented mainly by activities related to land use, occupation and transformation, and the related processes, notably the exploitation of natural resources, demographic changes, technological improvements, migratory patterns, societal conflicts, and communication networks. These activities fall into the category of niche construction (see below). Rather than a merely descriptive unit, the landscape is considered as an ecological component, that is, a functional entity formed by the assembly of the different ecosystems that live together in a given region and interact with each other. In terrestrial ecosystems, vegetation is a major landscape feature and its dynamics over time and space is commonly used as a proxy for general landscape dynamics.

Internal feedbacks within E, H, and L influence the state of each of these subsystems and, therefore, the nature of the interactions among them (external interactions). A relevant feature of internal and external feedbacks is the occurrence of amplification mechanisms that can lead to unexpected outputs as a result of nonlinear responses. For example, a shift to more arid climates (E) can cause changes from forested to more open landscapes (L), which may increase evaporation and enhance local climatic aridification, thus amplifying the initial climatic signal and triggering positive feedbacks that can eventually lead to desertification. In this case, climate is the initial forcing factor, but landscape features also influence climatic trends at local and regional scales. Similar amplification processes can occur between H and L in the case of human deforestation by fire, which enhances vegetation flammability and exacerbates fire proliferation. The concurrence of climatic dryness and human deforestation is an example of synergy, in this case between E and H acting on L, whose devastating potential is notably enhanced by the coupling of multiple feedbacks among the three subsystems. In this case, landscape changes (L) affect both climate (E) and humans (H), as deforestation patterns may influence, for example, human settlement, demography, and land use.

2.3 Niche Construction

A singular distinctive feature of socioecosystems is the human ability of modifying the environment and the landscape, whenever possible, or to adjust social and cultural performance to abrupt and unpredictable environmental shifts, if they occur. This capacity, intimately linked to human creativity and ingenuity, introduces new feedbacks within the E subsystem and in the relationships between the other EHLFS components. The modifications introduced by humans in the socioecosystem are known as niche construction and are absent in a hypothetical ecosystem without human influence (Rull 2021). Niche construction (NC) is an important process within ecodynamic relationships that allows those solutions to be made explicit. By studying the accumulated cultural and environmental changes, or “ecological inheritance” (Quintus and Cochrane 2018) we can identify the selective pressures that people and organisms experienced. To achieve this, we follow Odling-Smee et al. (2003) and Huebert and Allen (2020), who differentiate “inceptive” niche construction (INC) from “counteractive” (CNC) and “proactive” niche construction (PNC). Within INC construction processes of relocation and perturbation are key. These could involve the relocation of introduced cultigens to new environments, or the development and retooling of agricultural or other procurement practices. Inceptive niche construction can also involve perturbations like the firing or removal of vegetation and subsequent soil erosion, which in some contexts has detrimental effects and in others creates productive agricultural zones for economic species (sensu Spriggs 1997). CNC involves responses to ongoing environmental changes and tend to be conservative or stabilizing. This form of NC can restore previously developed food procurement practices, for example, when terracing is extended to accumulate sediments for the construction of gardens of existing cultigens. PNC involves innovations used to solve emergent or anticipated environmental problems or enhance resources (Huebert and Allen 2020), for example, the creation of new gardening infrastructure (e.g., rock gardens) or the increased focus on specific productive species.

3 Development of Easter Island's Socioecosystem During the Last Millennium

Easter Island has been a favorite case study to illustrate the application of the EHLFS approach. However, only the general features of this framework could be appreciated due to the lack of a robust and generally accepted chronology for the island's prehistory (Rull 2020b). Here a different strategy is used, which is more consistent with a HE analysis. The basic idea is that the EHLFS system can exhibit different configurations (states) depending on the interactions between the E, H and L subsystems, and these states gradually transform with time. In this way, a continuum of changing conditions rather than a succession of normative phases may be defined that characterize the evolution of the particular Easter Island socioecological system as a whole.

The first step of this analysis is to select the environmental (mostly climatic processes and geological features), human (notably cultural technologies and demography) and landscape (mainly deforestation patterns and land use) processes known to have occurred on the island and their most accepted duration in time in a sequential manner. For this purpose, the chronological framework introduced by Rull et al. (2016) is used as a basis, and new age determinations from a number of chapters of this book have been added. The chronological synthesis is depicted in Fig. 24.2, where six states have been distinguished and are described below in more detail. The chronological boundaries of these states should be considered indicative, rather than strict dates defining historic/prehistoric phases or periods.

3.1 State 1 (ca. 800–1175 CE)

Environmentally, this state was characterized by a warm and dry climate typical of the Medieval Climate Anomaly (MCA) and sea levels higher than present ones, which would have favored long-range navigation and facilitating the Polynesian colonization of the eastern Pacific islands and archipelagos, including Easter Island (Nunn 2007). The precise settlement date of Rapa Nui is still debated. While archeological colonization (sensu Hunt and Lipo 2018) seems to have occurred in the twelfth/thirteenth centuries (Wilmshurst et al. 2011), paleoecological evidence would be consistent with an earlier discovery, probably by intermittent human populations, as first proposed by Mann et al. (2003).

A pre-twelfth century arrival is supported by forest disturbance of the last millennium recorded in the sediment cores at Rano Kao, where dense palm forests were transformed into open palm woodlands at some unknown time before ca. 1050 CE (Fig. 24.2). Therefore, the possibility of early human influence in the SW part of the island could not be ruled out (Seco et al. 2019). It is also possible that the extended MCA drought could have contributed to forest clearing. Probably, synergies (S) between arid climates (E) and anthropogenic deforestation (H) con-

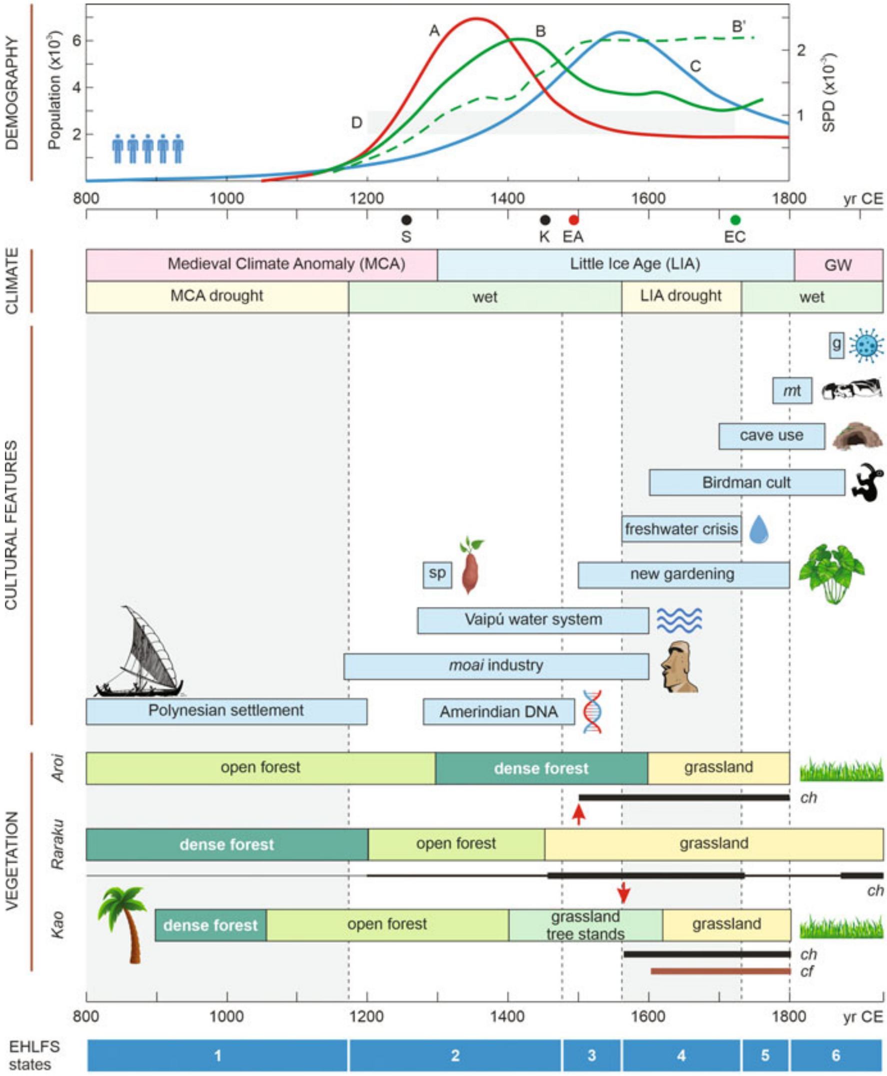

Fig. 24.2 Synthetic chronology of environmental (E), cultural (H) and landscape (L) patterns on Easter Island during the last millennium, based on several chapters of this book and other references. Six EHLFS states (1 to 6) are distinguished, which are displayed in detail in Fig. 24.3. Demographic curves: A, Brander (this volume); B, Lima et al. (this volume); B′, Lipo et al. (this volume); C, Steiglechner & Merico (this volume); D, Lipo et al. (this volume). Black dots, volcanic eruptions (Sáez et al., this volume); red dot, Europe-America contact (1492 CE); green dot, European contact (Easter Island, 1722 CE). Cultural features: g, genocide (Boersema 2015); *m*t, *moai* toppling (Fischer 2005); Birdman cult (Robinson and Stevenson 2017); freshwater crisis (Rull 2020d); sp, introduction of sweet potato (Muñoz-Rodríguez et al., this volume); new gardening (Steiglechner & Merico, this volume); Vaipú water system (Mieth et al., this volume); *moai* industry (Van Tilburg 1994); Polynesian settlement (Flenley and Bahn 2003; Hunt and Lipo 2006; Kirch 2010; Wilmshurst et al. 2011); Amerindian DNA (Thorsby 2016). Vegetation reconstructions: Aroi (Rull et al. 2015); Raraku (Cañellas-Boltà et al. 2013); Kao (Seco et al. 2019); ch, sedimentary charcoal; cf, spores of coprophilous fungi; red arrows, eventual population movements

tributed to the Rano Kao forest decline (L). In this case, active deforestation would have progressed without the aid of fire, as no sedimentary charcoal was recorded. Regarding feedbacks (F), aridification would have increased evapotranspiration, thus amplifying forest dryness and favoring its decline, with or without the aid of the above-mentioned anthropogenic synergies. However, the Ranu Raraku and Rano Aroi forests and woodlands remained untouched, which suggests that Rano Kao disturbance was a local phenomenon and difficult to explain with only climatic arguments. Among the demographic models gathered into this book, only the agent-based model of Steiglechner & Merico considers the possibility of an early human presence (Fig. 24.2).

The terrestrial landscape of Rapa Nui had little to offer the founding settlers in terms of humanly edible foods. Nesting sea birds were likely plentiful and a now-extinct ground rail was present (Steadman et al. 1994). There were no trees or plants with edible fruits and the species diversity of fish was lower compared to islands in warmer waters to the west. All of this was likely known prior to arrival as a result of exploratory voyaging before settlement. The first few decades would have been a period of inceptive niche construction as the Rapanui explored the variability in the island's avian, marine, geological, soil, and water resources. During this beginning of the colonization period, new cultigens and animal domesticates (e.g., chicken, Polynesian rat) were introduced to Rapa Nui that formed the economic base for the next six-hundred years. The agricultural system was supported by the mining of obsidian and basalt source material for tools from deposits around the island (Stevenson et al. 1984; Simpson and Dussubieux 2018).

3.2 State 2 (ca. 1175–1480 CE)

This state was characterized by an exponential growth of the Rapanui population, as shown in most demographic models (Fig. 24.2). Towards the end of this period, larger scale religious architecture began to be built and adorned with *moai*. This development occurred under a wet climate and abundant freshwater availability, which would have favored agricultural success and cultural development (Cañellas-Boltà et al. 2013). In spite of favorable climatic conditions, forests underwent a significant size reduction in Rano Kao and Rano Raraku, where forests were replaced by grasslands with scattered tree stands (Fig. 24.2). The occurrence of sedimentary charcoal within these crater lakes points towards active anthropogenic deforestation of these landscapes. In contrast, Rano Aroi forests underwent a significant expansion and/or densification, which was likely promoted by the wet climates, in the absence of anthropogenic indicators (Horrocks et al. 2015). Evidence for Polynesian contact with Amerindians has been evidenced by the arrival of the sweet potato (ca. 1300 CE) (Horrocks and Wozniak 2008) and the occurrence of Native American DNA of similar age in present-day islanders (Thorsby 2016). Some demographic models situate the population maxima (ca. 5000 to 7000 people) during this state (Fig. 24.2).

In this state, the human component seems to have been more decisive. Wet climates (E) would have been favorable for both forest growth (L) and the expansion of human populations (H). However, the active human contribution to forest clearing (probably for cultivation purposes, among others) overcame the potential climatic benefits for forest growth, which created positive feedback between human growth and land use that exacerbated forest decline (Fig. 24.3).

During this state, humans were actively engaged in an extended period of inceptive niche construction to create an agricultural system that could support a growing population. Inceptive behaviors included extensive deforestation of the palms and plant understory (Orliac 2000) through the use of slash and burn methods (Mieth and Bork 2018). Tuber cultivation was conducted in more open fields, or in lower density stands of forest that would have buffered the direct sunlight, winds, and helped retain moisture within Rapa Nui's porous volcanic ash-derived soils (Stevenson et al. 2018).

A high rate of population growth may have required more proactive niche construction efforts near the end of this period. One recognized strategy was to establish remote field systems above 200 m where rainfall amounts were substantially increased over the coastal plain. This would have lowered the water stress on tubers and facilitated full plant maturity that led to a more predictable yield. However, greater caloric returns on planting efforts may not have been forthcoming since soils become progressively nutrient poor with elevation through rainfall leaching (Ladefoged et al. 2013).

Settlements in this upland area of Maunga Terevaka lack the full complement of domestic features. Chicken houses (*hare moa*), enclosed gardens (*manavai*), and stone-lined earthovens (*umu pae*) are not present in a distribution of features consisting of small huts, house patios, terraces, and rectangular houses. Producing a harvest in this area is likely to have been important if the interpretation of the rectangular houses as elite management dwellings is correct (Stevenson et al. 2004).

A very important development started at ca. 1270 CE, in the form of a monumental water sanctuary on the southern slope of Maunga Terevaka Vogt and Kühlem (2018). This complex was built at approximately 250 m elevation in the seasonal Vaipú creek, which originated in the Rano Aroi bog. The Vaipú complex was used as a ritual precinct and could reflect a focus on the concepts of human fertility and rejuvenation (Mieth et al., this volume). It is unclear at the moment the motivations for this sustained effort.

3.3 State 3 (ca. 1480–1570 CE)

This state represents a short (less than a century) duration but exhibits evidence for several intense reorganization events. Rano Raraku, the quarry of the *moai* and a core feature of Rapa Nui ancestor worship, was totally deforested by humans, and a formerly scattered cultivation technique consisting of rock gardens began to dominate agricultural production on the island (Ladefoged et al. 2013; Stevenson

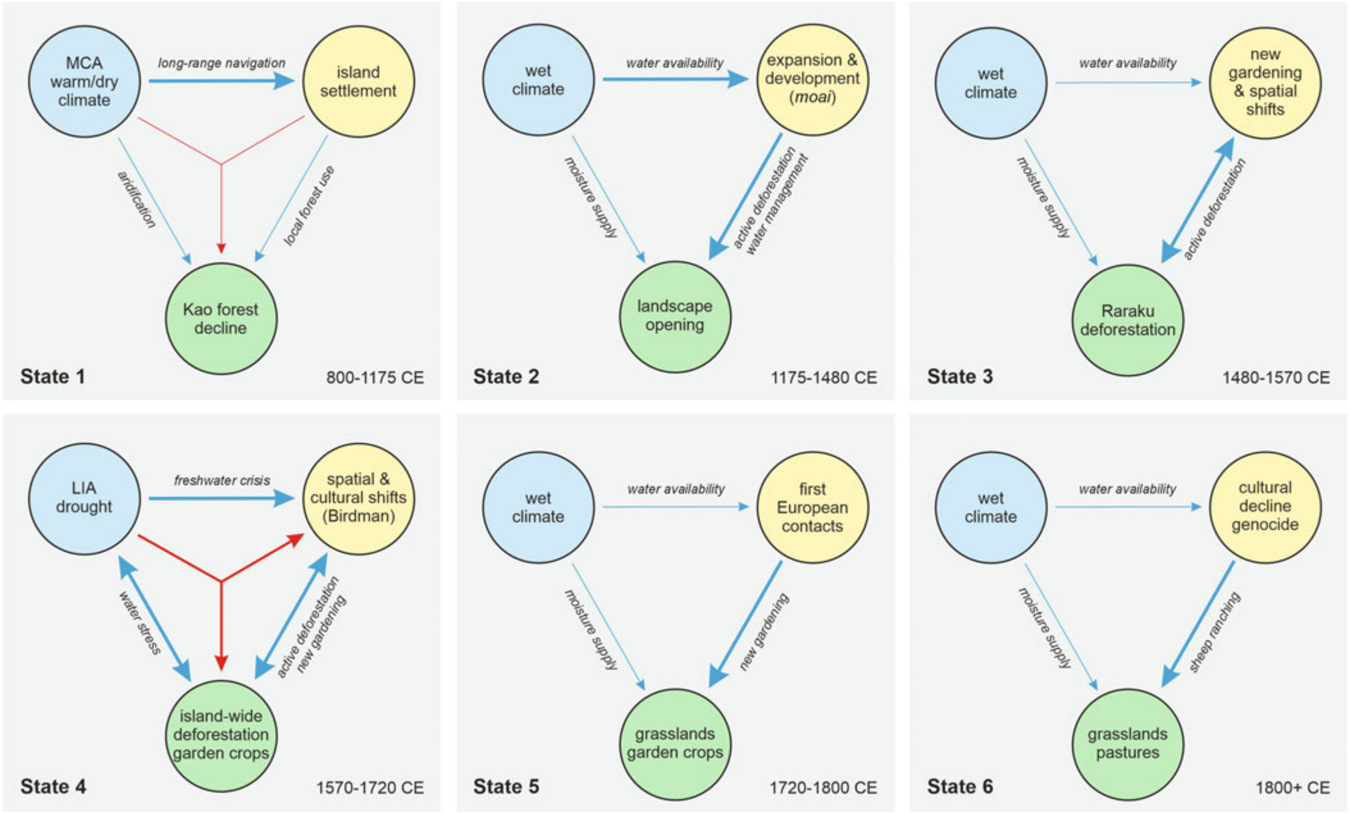

Fig. 24.3 Different states of the EHLFS system (socioecosystem) identified on the prehistory of Easter Island, based on the chronological summary of Fig. 24.2. The width of the arrows is related to the intensity of the processes they represent

et al. 2006). Rock-covered fields were created by the active mining of surface outcrops in order to create more favorable conditions for plant growth. Lower rates of evaporation led to higher soil humidity which favored microbial activity and soil health. The planting and harvesting of tubers with digging sticks and hoes would have let to basalt pulverization and mineral amendments such as calcium that contributed to overall plant health in the long term (Vitousek et al. 2014).

At the same time, the Rano Aroi forests began to be cleared using fire (Rull et al. 2015), and the first signs of cultivation appeared at this higher elevation (Horrocks et al. 2015). Climate remained wet and freshwater availability was still suitable for forest growth. This may be interpreted as a transitional state in which the Rapanui looked for alternative resources after the removal (or near removal) of the Rano Kao and Rano Raraku forests. These alternatives were to use other still untouched forests (Rano Aroi) and to further develop an extensive network of rock garden sites for cultivation. The demographic models that situated maximum population levels in State 2 show a significant decline in State 3, whereas others estimate that population maxima would have occurred during State 3 (Fig. 24.2).

The Vaipú water ritual precinct, experienced a catastrophic runoff event dated to 1480–1600 CE (Mieth et al., this volume), which roughly coincides with the time interval corresponding to this stage. As a result, most of the monumental structures were destroyed and the ritual activities were interrupted. However, the site was not abandoned and continued to be used for horticultural purposes (Mieth et al., this volume). This is consistent with the above observations of increased forest disturbance and cultivation around the Aroi bog.

Humans (H) were still the main actors in this state, and deforestation (L) continued under a maintained climatic wetness (E). However, forest degradation led to the search for alternative resources by dramatically increasing the extension of cultivated lands. In this state, the main feedbacks were between forest clearing and rock garden development, which reinforced each other (Fig. 24.3). No clear synergies between E, H, and L can be observed.

3.4 State 4 (ca. 1570–1720 CE)

The beginning of State 4 is characterized by the occurrence of an intense drought during the Little Ice Age (LIA), which caused the drying out Lake Raraku for more than a century and a half (Cañellas-Boltà et al. 2013). By this time, the island was totally deforested using fire and transformed into a near-treeless grassland (Rull 2020c). The deforestation of Rano Kao had progressed slowly but at the beginning of State 4, anthropogenic forest clearing intensified, as suggested by the abrupt charcoal increase and the appearance of spores of dung fungi (*Sporormiella*), which are indicators of human presence (Seco et al. 2019). This suggested that human occupation of Rano Kao intensified during the LIA drought and witnessed the development of intensive cultivation of the crater lake shore (Horrocks et al. 2012).

The lack of rainfall for over 100 years must have been a great hardship for Rapanui farmers. Rock garden infrastructure, which had been in place for several centuries, served as an effective moisture conservation strategy, especially in fields with the heavier lithic mulch. But many fields have only shallow veneer and boulder coverings (Stevenson and Haoa 2008) that are less effective. As a result farming most certainly became increasingly risky with crop yields declining and we could hypothesize that proactive niche construction efforts such as lithic mulching, applied to create a more effective barrier to moisture loss, became more widely implemented.

However, population responses may not have been only technological or influenced solely by limited moisture. Stevenson et al. (2015) used obsidian hydration dates from the domestic settlement pattern across Rapa Nui to show how variation in regional landscape use reflected human settlement decisions over time. Their analysis suggested that during the pre-contact drought of State 4 that land use was not sustainable across all of Rapa Nui and decline occurred in some dry (under current conditions) near-coastal locations on the west coast and wetter but infertile parts of the Maunga O'koro upland area. Post-contact increases in settlement density occurred at locations of both adequate moisture and more fertile soils and lasted until the 1860s CE. Implied by these selective patterns of settlement are conscious decisions by people to find niches favorable to agriculture and human well-being.

Other proactive niche construction activities at this time must certainly have centered around water management technology, but no obvious archeological indicators such as large cisterns are visible within the domestic settlement pattern. However, it is our hypothesis that the circular garden enclosure, or *manavai*, was developed at this time as a nursery or growing area which protected plants from drying winds and raised the humidity and soil moisture level within the enclosure. An excavation within a *manavai* (misidentified as a house feature) by Ferdon (1961b) revealed the soils to be deep (60-80 cm), without stratigraphy, and with numerous pockets of charcoal and soil which could have been soil nutrient amendments. There has been no direct dating of this feature type, but their well-conserved condition for many features (Stevenson and Haoa 2008) argues for their use in late prehistory.

Alternative freshwater sources have been proposed for the LIA drought, notably coastal fresh/brackish water seeps (Brosnan et al. 2018) and the Rano Kao lake (Rull 2020d), which was likely the only permanent freshwater body of the island during this intense and prolonged drought. It has also been suggested that *ahu* monuments could have acted as markers for the location of water sources, both at interior cinder cones (Stevenson 1997) and at coastal seeps (DiNapoli et al. 2019). The intensified use of the Rano Kao crater converges with the building of a small *ahu* and plaza on the western crater rim at 'Orongo around ca. 1600 CE, providing another example of ritual marking. Obsidian hydration dates and radiocarbon dates show sustained activity at this locality from this point onward, although the types of structures and rituals are not known (Robinson and Stevenson 2017). What accounts for this reorientation may be a long and intense freshwater crisis, which was a major disruption on an island as Rapa Nui, where the porous volcanic rocks hinder the occurrence of permanent surface freshwater ponds and streams (Herrera and Custodio 2008).

The larger picture is interpreted as a relocation of the Rapanui religious center from Rano Raraku to Rano Kao, which is likely linked to the availability of freshwater, as Rano Kao was now the only on-shore freshwater source on the island (Rull 2020d). The strength of the Birdman concept in Rapa Nui society is documented by Sherwood et al. (2019), who dates the application of Birdman images on two standing *moai* in the Rano Raraku interior to just before European contact (1722 CE). The new social and political order expression at ‘Orongo, along with the continued use of *rock garden* cultivation, could have facilitated the continuity of the Rapanui society without significant demographic declines (Mulrooney 2013; Stevenson et al. 2015; Jarman et al. 2017; Wozniak 2017). A number of the available demographic models, including some published in this book, hypothesize this period coincided with a significant decline of the Rapanui population (Fig. 24.2). However, according to Lipo et al. (this volume), these models seem to have little archeological or historical support.

This is a more complex state of the EHLFS system, which was largely due to the combined action of a climatic drought (E) and the total deforestation (L) of the island by humans (H). The synergies between these processes have consequences for both the landscape and Rapanui society, on an island devoid of forests and under a pronounced freshwater crisis. The feedbacks between deforestation and rock garden cultivation continued and new feedback between climatic drought and deforestation was added, as occurred in State 1 (see above).

Regarding internal subsystem feedbacks, the human component developed a new strategy of spatial shifting (i.e., ending the Rano Raraku quarry as the cultural core), likely in the search of freshwater. This may also have included cultural changes, notably less emphasis on ancestor worship and the establishment of the Birdman cult on the rim of Rano Kao crater (‘Orongo); although the chronology of this transition requires refinement (Stevenson et al., this volume). This cultural shift has been considered an adaptation to changing environments, and carving activities could not be recreated due to the lack of suitable rocks (tuff) to carve the *moai* in the basaltic Rano Kao crater (Rull 2016); which can also be considered part of the environmental subsystem (E) of the EHLFS system. Therefore, State 4 represents the most complex and dynamic state of the socioecosystem of Easter Island, where all subsystems interact and develop several types of internal and external feedbacks and synergies (Fig. 24.3).

3.5 State 5 (ca. 1720–1800 CE)

This state was marked by the end of the LIA drought and the beginning of a new wet climatic period coinciding with the arrival of the first Europeans (Fig. 24.2). The island was near-totally deforested and the first visitors found a society that cultivated the land, lived in thatched dwellings and lava-tube caves (Ciszewski et al. 2009). The available paleoecological record ends at this point, except in Rano Raraku, where no significant changes are observed.

For the first time, societal stressors have an external human origin. The first European explorers appeared to have profoundly impacted Rapanui culture, starting with the killings upon Roggeveen's initial shore landing and continuing with later kidnappings and hostilities that eventually generated an incipient xenophobia near 1800 CE (Richards 2008). This fear of outsiders may also have arisen from the transmission of communicable diseases. According to Hunt and Lipo (2011), this could have been initiated between the visits of González de Haedo (1770 CE) and James Cook (1774 CE). Although the causes are uncertain, the limitation of outsider contact clearly reflects proactive steps to preserve the integrity of Rapa Nui society.

However, in the first century after contact, there is also evidence for an indigenous affinity for western visitors. Ship petroglyphs are rendered on the torso of a *moai* at the Rano Raraku statue quarry (Skjoldsvold 1961) and on walls within coastal caves (Lee 1992). Paintings in the houses at ‘Orongo show European ships (Ferdon 1961a; Routledge 1920) and large earthworks (*miro o'one*) (McCoy 1976; Stevenson and Haoa 2008) and burial chambers (*ahu poepoe*) (Shaw 2000) take the form of European sailing vessels (See Stevenson et al., this volume). Strategies of niche construction during this period could reflect a proactive response to high levels of disease. This is inferred from an emphasis on fertility as represented by the hundreds of incised vulvae on boulders and in caves (Lee 1993), a transition in worship from an emphasis on (failed) ancestors to greater deities (*Makemake*) as part of the Birdman Cult, and leadership based not on genealogy but awarded for competitive strength and achievement. We hypothesize that ritual activities surrounding the Birdman Cult intensified at ‘Orongo as a mechanism to cope with widespread population illness, personal anxiety, and a high death rate.

The arrival of the first Europeans may be considered as and external input to the local EHLFS system or part of the environmental subsystem (E). No matter the choice, the consequences were the same. The arrival of these first visitors coincided with the return wet climates (E) to a totally deforested island (L). However, in spite of these relevant events, the landscape features remained the same, but population dynamics were elevated. In contrast with the former state (4) the EHLFS system was simple, without any evident feedbacks and synergies in the landscape and environmental subsystems. The human subsystem, however, was exceptionally responsive to external stressors (Fig. 24.3).

3.6 State 6 (ca. 1800+ CE)

The situation changed radically with the frequent arrival of adventurers, whalers, traders, and slave raiders, who totally disrupted the traditional Rapanui society. Virtually all *moai* monuments were toppled during this state (Cauwe, this Volume; Fischer 2005). The culmination of this turmoil was the drastic reduction of the island population to around 110 individuals, mainly due to the introduction of alien epidemic diseases (smallpox, syphilis, tuberculosis). This decimation of Rapanui culture occurred between 1862 and 1877.

In this state, the climate (E) and the landscape (L) remained essentially the same, but the human component (H) experienced dramatic changes, which could be considered internal feedbacks or environmental stresses, as the new visitors were occasional and looking only for local material (water, food) and human (slaves) resources, rather than for a place to establish themselves. After the Rapanui genocide, the situation was very different, but this is part of the modern history and, hence, it does not fall within the aims of this book.

4 Summary

Six different states constituting the prehistoric socioecosystem (sensu Barton et al. 2004) of Easter Island have been identified using the EHLFS (Environmental-Human-Landscape Feedbacks and Synergies) approach (Rull 2018). The system was relatively simple, with just a few feedbacks and synergies among the E, H, and L subsystems) during the Polynesian settlement and the elaboration of ancestor worship and development of megalithic architecture (States 1 to 3). Maximum complexity was attained in State 4 (ca. 1570 to 1720 CE), which was characterized by intense feedbacks and synergies among climate, humans, and landscape, which led to a spatial and cultural reorganization of the ancient Rapanui society. This was followed by again low-complexity but highly dynamic states (5 and 6). The succession of socioecosystem states before and after maximum complexity (State 4) was significantly different. Although these states occurred mostly under wet climates, they strongly differed in the dynamics of human and landscape elements. Before State 4, Rapanui society was growing relatively fast, developing investing in megalithic architecture and clearing the forests. After State 4, the Rapanui society cultivated a totally deforested island until European arrival, which was the beginning of a total sociocultural disruption.

5 Final Remarks

The holistic approach presented here should be considered a first attempt to be modified and improved as more information and more ideas are incorporated into the knowledge of Rapa Nui's prehistory. This synthetic framework should also serve as an experiment to be criticized, and eventually abandoned, on the way towards better and more sophisticated and quantitative approaches. For example, it is possible that some modelers may find the approach interesting and develop explanatory and/or predictive models to test socioecological hypotheses on the island. In any case, a starting point is needed for further development. All we hope is that critics have the same spirit as we have had at presenting the model with a constructive attitude aimed at obtaining the best approach possible. The multiple working hypotheses framework (Chamberlin 1965) and the strong inference method of hypothesis testing (Platt 1964) may provide the necessary tools for improvement (Rull 2018), but nothing can replace the good faith of researchers and their truly scientific mindset. We encourage the organizers of scientific meetings on Rapa Nui (Easter Island) to dedicate an open session to discuss island's prehistory under a holistic perspective, including as many disciplines as possible.

Acknowledgments The authors are grateful to Thegn Ladefoged for his useful comments and insights on a previous version of this manuscript.

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