Chapter 3
Perspectives for the Study of the Galapagos Islands: Complex Systems and Human–Environment Interactions

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Introduction

“Enchanted Islands,” “Ecological Paradise,” “In the Footsteps of Darwin”—we have been intrigued by these, and many other, colorful descriptions of the Galapagos Islands and have enjoyed the many declarations of the islands’ mysterious uniqueness, well proclaimed by ancient mariners, explorers, pirates, and scholars. Their accounts are testimony to the presence of the “Imps of Darkness” and the “Fire in the Earth,” as new species and new landforms combine to create a landscape and seascape populated by endemic inhabitants who have evolved and adapted in very remarkable ways in response to a dynamic environment. In recent times, the hushed mention of “Paradise Lost” and “Paving of Paradise” has become part of the contemporary story of the Galapagos Islands, a story often muted by the amazing descriptions of the iconic and emblematic species that help define the islands and add to their mystery. But with all the splendor and majesty, the Galapagos Islands are in crisis; a crisis born of the very success that the archipelago has enjoyed in maintaining its native and endemic species at which the world marvels. Historically protected through geographic isolation, the islands are no longer remote; they are now explicitly connected to the global economy and to international tourism markets. Modern travel has effectively created a “land bridge” that connects the

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Galapagos to the world community, with all of its consumptive demands, threats of invasive species, and tourists craving additional services and richer experiences, generally accommodated by an influx of people mostly arriving from mainland Ecuador, who seek better jobs and improved economic opportunities in the tourism industry. Eager to visit, experience, and/or work in the Galapagos Islands, the residential and tourism populations have substantially increased over the past 20 years, approaching 30,000 residents and 185,000 visitors as of 2011.

Today, the Galapagos Islands must rely upon adaptive and participatory management and enlightened public and environment policy to ensure their survival. The direct and indirect consequences of the expanding human imprint have signaled a concern about the future of the Galapagos. In this interconnected world, the "Galapagos Paradox" will surely be tested—how can the Galapagos Islands be protected from the many endogenous factors and exogenous forces that shape, reshape, and often debilitate many island ecosystems? Can the Galapagos Islands accommodate the increasing levels of tourism, local development, and population migration associated with new residents and international visitors? Drawn by the many attractions of this special place, some are seeking economic rewards, while others seek rewarding ecological experiences and the promise of an ecosystem at peace with its surroundings. The very features and specialness of the Galapagos that attract visitors from around the world and create employment opportunities, mostly in tourism for a migrant population, are the same forces that put stress on vulnerable settings and make island sustainability often just a dream. The challenge is to create a comprehensive and adaptive model of the Galapagos that effectively integrates people and the environment within a complex and dynamic system, where critical thresholds, feedback mechanisms, and nonlinear relationships are recognized within the context of social–ecological dynamics and the factors that induce changes in system behaviors and chart alternate trajectories of the future. We term the interactions between people and environment and their link effects *Island Biocomplexity*, a new framework and perspective for the study of social and ecological systems in the Galapagos Islands and other similarly challenged island ecosystems around the globe.

Study Area

The Galapagos Islands are a "living laboratory" for the study of evolution, environmental change, and conflicts between nature and society. Free from human predators for almost all of their history, these islands have developed some of the most unique life forms on the planet, adapted to their harsh surroundings and living in ecological isolation. It was not until Charles Darwin's famous visit in 1835—which helped inspire the theory of evolution—that the islands began to receive international recognition. The Galapagos Archipelago encompasses 11 large and 200 small islands totaling approximately 8,010 km^2.

In 1959, the Galapagos National Park (GNP) was created, and in 1973, the archipelago was incorporated as the twenty-second province of Ecuador. UNESCO designated the Galapagos as a World Heritage Site in 1978. The islands were further deemed a Biosphere Reserve in 1987. In 1998, the Ecuadorian government enacted special legislation for Galapagos in an effort to promote both conservation of terrestrial and marine biodiversity and sustainable development. The Special Law for Galapagos characterizes introduced species as the principal obstacle to the aim of harmonious coexistence between people and the unique flora and fauna of Galapagos. The Special Law is now being revised as a consequence of the new Ecuadorian constitution that was approved in 2008 through a national referendum.

The Galapagos National Park comprises 97 % of the land areas of the archipelago. The remaining 3 % includes urban areas and agricultural zones. The Special Law implemented a registration system in 1998 to monitor the existing human population in the islands. A more rigorous registration system that tracks movement in and out of the Galapagos is now being implemented. Currently, the Special Law defines four types of people: (1) undocumented or "illegal" workers from the Ecuadorian mainland, (2) "permanent residents," (3) "temporary residents" or workers subject to legal residence restrictions of labor contracts, and (4) "tourists."

During the past three decades, dramatic social–ecological changes have threatened the social, terrestrial, and marine ecosystems of the Galapagos. Beginning in the 1970s, the islands started to experience exponential population growth. Thousands of new residents began to migrate from the mainland, attracted by the promise of lucrative opportunities linked to the islands' rich marine and terrestrial ecosystems and "pushed" by the lack of economic opportunities in many parts of mainland Ecuador. The local population grew from under 10,000 residents in 1990 to nearly 30,000 in 2011. In addition to settlement and population in-migration, the number of tourists has increased from about 41,000 in 1990 to nearly 185,000 in 2011. Some of the more pronounced trends associated with increased human presence include (a) unprecedented use and extraction of terrestrial and marine resources, (b) introduction and proliferation of invasive flora and fauna that can replace native and endemic species, (c) increased degradation of fragile environments, (d) unprecedented energy consumption and waste generation associated with population and tourism growth, and (e) increased interinstitutional conflicts over governance and policy.

The Galapagos as a Socio-Environmental System

The links between people and environment in the Galapagos serve to frame the many conflicts between and among the various resource conservation and economic development sectors that often have competing interests. Historically, there have always been sectors of the local economy supported by agriculture, as well as by the fishing and tourism industries, but the rapid increase in the economic drivers associated with fisheries and tourism over the last 20 years has exacerbated an already difficult and complex situation. For instance, economic diversification from agriculture to tourism has led to labor shortages on the farm and a demand for mainland immigrants, and a decline in management of invasive species has led to land abandonment and the threat of invasive species "escape" from human use zones to the Galapagos National Park.

The primary decisions of concern at the individual and household levels are related to alternative strategies of household livelihoods and feedbacks to the intensification or abandonment of agricultural activities in response to changing economic opportunities. An important landscape dynamic is the arrival and spread of invasive species. The primary exogenous influences include the changes in the intensity and frequency of El Niño events and the growth of tourism in the islands and related consequences for alternative household livelihood strategies. As tourism increases, it alters the economic and demographic processes at the household level that subsequently affect the way that households manage the landscape.

The ecological system is the focal point of international interest in the Galapagos. Among the greatest threats to the ecosystem of the Galapagos is the growing number of exotic plant and animal species (Mauchamp 1997; Tye et al. 2002; Tye 2006). Increased human presence has hastened the introduction of invasive species that are now so prevalent that they threaten the native and endemic flora and fauna of the islands and significantly impact the human population. The problem of invasive species illustrates the important feedbacks between the social and ecological systems: land management practices reflect human migration patterns and economic choices, whereby increasing urbanization is linked to tourism and other opportunities that render lands underutilized and abandoned, becoming fertile ground for invasive species. To the fragile ecosystem of the Galapagos, these invasive plants change the biological diversity, degrade ecological services, reduce the number of endemic plants, change grasslands to forests, modify ecological processes, and compete with other species.

Complexity Theory and Agent-Based Models

Complexity theory sees the complex nature of systems as emerging from nonlinearities due to interactions involving feedbacks occurring at lower levels of social and ecological organization within the system (Cilliers 1998; Malanson 1999; Matthews et al. 1999; Manson 2001). Complexity draws on theories and practices from across the social, natural, and spatial sciences (Parker et al. 2003). Of particular interest have been the characterization of spatial patterns and links to processes, feedback mechanisms and system dynamics, and space-time lags and scale dependencies of processes and actors (Evans and Kelley 2004; Malanson et al. 2006). Complexity science offers a new science epistemology focusing on the creation of order by self-organizing heterogeneous agents and agent-based models. The fundamental element of complex systems is the adaptive behavior of human–natural environments (Parker et al. 2003) and how agents learn, react to new conditions, alter relationships with a changing environment, and mediate their behavior relative to external forces, such as climate change and public policy, and endogenous factors, such as the spread or eradication of invasive species.

Agent-based models (ABMs) are constructed in a “bottom-up” manner by defining the model in terms of entities and dynamics at a micro-level, that is, at the level of individual actors and their interactions with each other and with the environment (Epstein and Axtell 1996; Parker et al. 2003; Brown and Duh 2004; Brown et al. 2005). ABMs consist of one or more types of agent embedded in a non-agent environment. Agents may be individuals (e.g., householders, farmers, fishers) or institutions (e.g., a local government, conservation NGOs, firms). The state of an agent can include various characteristics, preferences, and memories of recent events, as well as particular spatial and social connections. Agent definitions include their capabilities to carry out particular behaviors as well as their decision-making rules, heuristics, learning, and other mechanisms, which the agents use to generate their individual behaviors in response to inputs from other agents and from the environment. Often, empirical data are used to establish the initial conditions of the system, specifying the initial attributes of an agent that include type characteristics, intrinsic behavioral rules, modes of communication and learning, and internally stored information about itself and other agents (Tesfatsion 2003). The generation of different types of landscape patterns over space and time based on different theoretical approaches yields a set of future scenarios of change that can include endogenous changes and exogenous shocks and can alter trajectories of landscape change (Rindfuss et al. 2008; Mena et al. 2011).

A Model of the Galapagos Islands: An Example

Figure 3.1 is a conceptual model of the Galapagos Islands that we have created to demonstrate how complex systems and ABMs can be used to explore human–environment interactions and to test ideas about “what-if” scenarios of social and ecological change. It is a simplified view of the complex population–environment system in the Galapagos Islands. In the picture model, we have indicated several boxes that reflect the primary system components that we will consider. The boxes represent demographic, socioeconomic, and ecological subsystems of the broader system and are explicitly linked through flow arrows that indicate positive (+) or negative (−) relationships. Feedback loops are indicated by arrows that connect two boxes through positive and negative relationships. Between the boxes and associated with an arrow with either a positive (+) or negative (−) effect, we have indicated key processes worthy of empirical analyses to help define rules of behavior and sets of relationships, such as *migration*, *off-farm employment*, *agricultural markets*, *land abandonment*, and *management/genetic repository*. While exogenous factors are important to the behavior of the resource conservation and economic development system in the Galapagos Islands, we have tried to indicate only those that we will consider and then within a general way so that the system can be kept

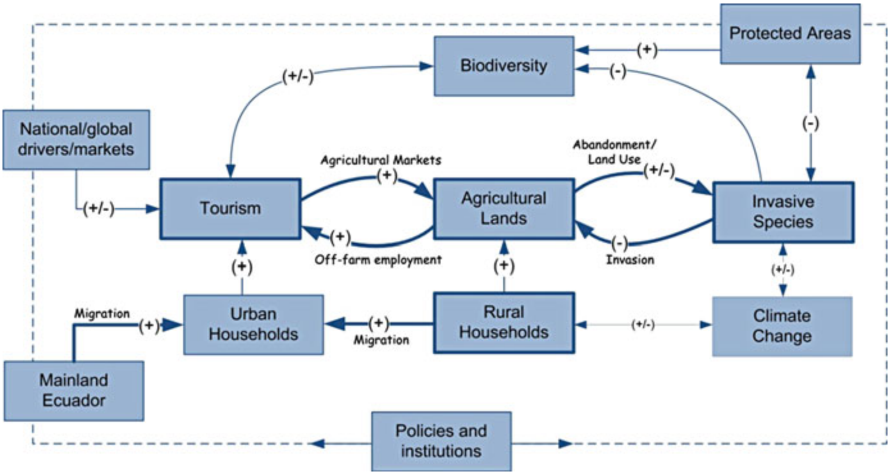

Fig. 3.1 A generalized system overview of human–environment interactions in the Galapagos Islands of Ecuador

relatively simple to demonstrate the alternative complexity theory context for addressing challenges to the Galapagos Islands. We include international organizations and national (including the Ecuadorian mainland) and local governments in our system as they affect policies, practices, and other institutions (e.g., the United Nations Development Program, Conservation NGOs). We also include climate changes (i.e., El Niño and La Niña events) as they have historically affected populations and biodiversity, the drivers of invasive species, the drivers of global and national markets for marine resources, and the adoption of fisheries as a household livelihood alternative. Further, fisheries and tourism are viewed through the lens of labor (i.e., employment opportunities), considered as part of alternative household livelihood strategies. Of particular interest is the impact of farm abandonment caused by the "push" of invasive plants and the cost and effort of eradication approaches, as well as the general lack of market integration of farmers to sell their products throughout the islands and on the mainland. The "pull" factors include the higher-wage employment opportunities in the tourism and fisheries sectors.

Using an ABM framed within complexity theory, we can spatially simulate population pressures as "shocks" to social–ecological systems to further assess, for instance, the impact of institutions and policies on the behavior of integrated systems. Within our models, we can, for instance, (a) increase the amount of visitors to the islands by 20 and 30 % or more; (b) allow more temporary labor into the islands from the mainland to work on farms and in the construction, tourism, fishing, and service industries; (c) increase the number of tour boat operators and the size of the boats, thereby accommodating more tourists and increasing the vulnerability of the social–ecological system; (d) increase or decrease the presence of tour operators and service providers of transnational companies; (e) vigorously enforce (and relax) fisheries' regulations for local/global operators; (f) reduce the frequency and intensity of El Niño events, thereby reducing the spread of invasive plant species and maintaining household participation in local fisheries that have global implications; and (g) increase the effectiveness of government policies that reduce immigration from the mainland and restrict international tourism.

A Galapagos Example of Scenario Testing Through an ABM

As an example as to how one can move from the theoretical to the applied, Miller et al. (2010) developed a virtual ABM for the Galapagos Islands—a model that represents key selected elements of the islands to test hypotheses and empirical relationships on system behaviors and dynamics. The ABM was designed to explicitly examine complex and dynamic systems in the study of coupled human–natural systems, with an emphasis on social–ecological interactions in the Galapagos Islands. The virtual environment was designed to maintain the fundamental characteristics of the Galapagos Islands without incorporating needless definition and "noise" in the geographic setting and the modeling environment (Walsh et al. 2009). The ABM examines the challenges of resource conservation and economic development on land use change, including, for instance, the spread of invasive plant species, and alternate household livelihood strategies, particularly employment diversification and job "switching" among the agricultural, fishing, and tourism sectors in the Galapagos, through a set of associated and modeled social–ecological "pushes" and "pulls" that affect human behavior and environmental dynamics. The spatial simulation model was designed to integrate disparate social and ecological data, organized within a GIS, to examine the interactions and feedbacks between people and environment in an island setting. The virtual model most closely resembles Isabela Island, which is geographically positioned in the western portion of the archipelago, populated by approximately 2,500 residents, and is a younger, more volcanically active island in the archipelago. With a coastal community and an agricultural zone in the highlands, residents and tourists move between the two settings to work on family farms and to experience important ecotourism sites, respectively. The virtual Galapagos is similar to actual conditions in that the primary tourism community is located along the coast, agriculture is restricted to the highlands, fisheries are primarily a near-shore activity, and the protected area envelops the human use zones.

Figure 3.2 shows the central elements of the generalized Galapagos model. It is designed to examine land use change—primarily the spread or contraction of the invasive species, guava, in the agricultural highlands—and the ability of island residents to switch between employment sectors in agriculture, fisheries, and tourism relative to new economic opportunities, such as additional jobs in tourism or in response to ecological disincentive, such as a reduction in local fisheries as a consequence of El Niño events. The agents are farmers in the agricultural zone, fishermen in the marine zone, tourism workers in the urban area, park employees in the protected area, and invasive guava that operates on the underlying environmental grid within the agricultural zone and the protected areas. Guava agents are controlled by

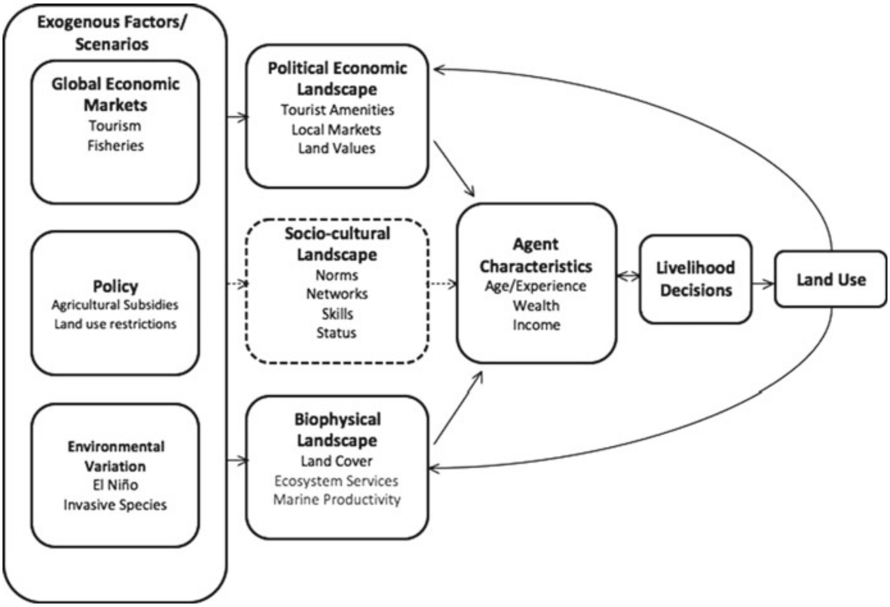

Fig. 3.2 Model design for a virtual Galapagos Islands (after Miller et al. 2010)

neighborhood effects, meaning that the spread of guava is influenced by the behavior of adjacent farmers and the characteristics of surrounding land parcels. Park agents are only involved in the eradication of guava and are free to move around the entire protected area.

The model acknowledges the importance of exogenous factors in shaping human conditions and the behavior of agents (Gonzalez et al. 2008; Walsh et al. 2011). External factors, such as global market conditions for fisheries and tourism, public policy regarding agricultural subsidies and land use restrictions, and environmental variations including El Niño–Southern Oscillation (ENSO) events and the spread or eradication of invasive species, all have the capacity to impact local socioeconomic (e.g., local market conditions and amenities for tourists), cultural (e.g., social networks and the sharing of information), and biophysical (e.g., marine productivity and ecosystem goods and services) characteristics of the Galapagos Islands. As agents (i.e., individuals and/or households) learn and adapt relative to exogenous forces and endogenous factors, they can choose to diversify their employment patterns by moving between agriculture, fisheries, and tourism, often engaging simultaneously in more than one livelihood alternative in response to dynamic social and ecological conditions. Agent characteristics, such as age, experience, education, wealth, income, and local knowledge combine to influence how social–ecological factors influence their thinking relative to the model outcomes that involve job switching, the accumulation of wealth, and land use change patterns, particularly those linked to the spread or eradication of invasive species on household farms.

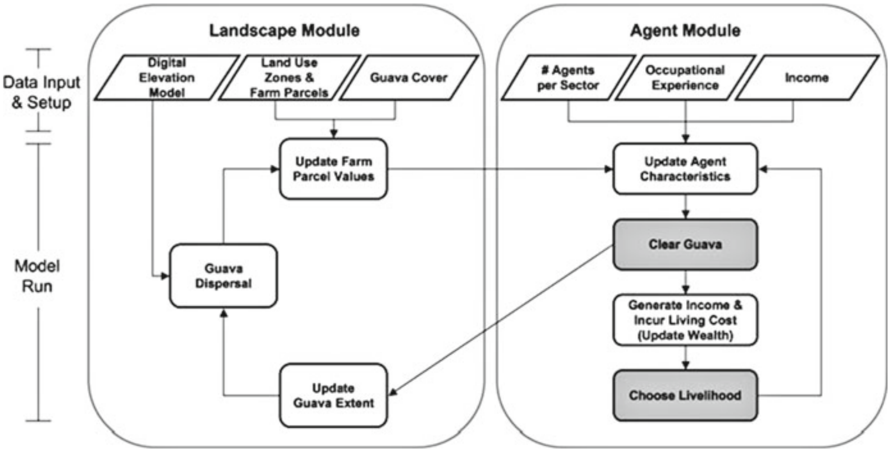

Fig. 3.3 Landscape Module and Agent Module (after Miller et al. 2010)

The model operates on an annual basis where a graphical user interface allows the analyst to interact with "real" data on farm locations, island population, land use conditions, tourism levels, and the number of licensed fishing boats through a series of levers or switches that increase or decrease variable magnitudes. The intent is to create a social–ecological laboratory in which scenarios can be examined by perturbing a base model. The accumulated wealth of agents is tabulated; job switches among agriculture, fisheries, and tourism are tracked; costs are incurred when agents move from one employment sector to another; trajectories of change in the environment are identified; and interactions between agents are observed as they learn and adapt to changing social and ecological conditions, such as the spread of invasive species on abandoned land, the eradication of invasive species on managed agricultural land, the adoption of public policies to encourage the return of farmers to their household farms through government incentive programs, such as farm subsidies, and the degradation or enhancement of marine and/or terrestrial environments as a consequence of El Niño or La Niña events. In short, the ABM has agents specified in space and time, and the environment is represented on a spatially referenced grid that serves as the physical space of social–ecological interactions of individuals and households with their environment.

Figure 3.3 shows the Landscape Module and the Agent Module (after Miller et al. 2010). The Landscape Module primarily involves the spread of guava. Without data on the spread rate and social–ecological factors that govern the behavior of guava on and off farms in the agricultural highlands, the areal expansion or constriction of guava is calibrated to mirror-observed rates of change from a satellite image time series. A Digital Elevation Model (DEM) is used to characterize terrain settings, important in land use change patterns. In addition, land use zones and farm parcel boundaries are defined through shapefiles organized within a GIS. The Agent Module primarily involves the behavior of farmers, fishermen, tourist industry workers (not tourists per se), and park employees, as well as the household livelihood decisions that the agents make, that is, remaining in or switching to alternative employment opportunities in fisheries, tourism, and agriculture, given financial motivations and ecological opportunities. The initial number of agents is taken from the 2006 population census for the Galapagos. The income of each agent is randomly selected from a livelihood-specific, truncated normal distribution based on the 2006 population census, and gross income is estimated, as is the agent's ability to switch between livelihood options, given potential and actual income levels. Agents can switch livelihoods based on a number of inputs: (1) expected number of tourists, (2) number of open fishing licenses, (3) selling price of fish and agricultural products, (4) start-up costs, and (5) cost of maintaining property. Agents can accumulate wealth according to livelihood decisions. Agent characteristics are updated relative to farm conditions and the areal extent of guava, for example, deciding to stay in agriculture and eradicating guava to enhance crop productivity. The cost of eradicating invasive species is calculated, negatively impacting living costs and household wealth, thereby influencing a farmer's decision to remain in agriculture or switch to fisheries and/or tourism, with associated costs.

Selected results from the hypothetical model indicate the following: the number of people working in fisheries remains stable across the 50 years of the model run, while the number of farmers initially declines as they transition to the tourism sector; the population in tourism and farming remains stable, except for small changes during El Niño years; tourism increases due to switching livelihoods during those years; some farmers "exit" the system due to low accumulated wealth and an inability to switch to alternate sectors; guava initially decreases and then increases, and by the end of the observation period, the area in guava is virtually the same as in the initial conditions. For the scenario involving a government-provided subsidy to promote agriculture in the highlands, the largest farm subsidy ($3,000) has the greatest effect on the population of farmers and the total area in guava; farmers increase in number, and employment patterns remain high throughout the study period; a collapse in global fisheries is accompanied with a decrease in farmers and fishers, while the number of workers in tourism increases and the median income in fisheries and farming decreases; and the area in guava decreases during and after the tourism decline. Lastly, for the scenario that examines a decline in tourism associated with a global economic slowdown, the number of workers in fisheries decreases during the period of low tourism revenues, and the number of farmers increases; as the tourism industry recovers from the economic crisis, the number of tourism workers increases, while the number of farmers decreases to near baseline levels; and guava shows a slight decrease during and after the tourism decline.

The Tourism System

Presently, tourism and all of its related goods and services form the major economic engine in the Galapagos Islands. The idea of the archipelago as a destination for nature-based tourism that would simultaneously advance economic development and support conservation is difficult to imagine right now. We are currently developing an agent-based model (ABM) to understand the future effects of different trends in tourism as the core feature of the socio-environmental system for the Galapagos Islands. We assume that, in the future, in great part, tourism in the Galapagos will be controlled by global forces, including the types of tourists who are willing to come to the Galapagos Islands and their expectations and willingness to pay for special services.

As we know from both the Galapagos and from other tourist destinations, different types of tourism evolve over time (Vera et al. 1997). Tourism in the Galapagos can be divided into four phases. First, when the tourist sector started to develop in the late 1960s, emphasis was entirely placed on overnight boat tours, a model that was promoted under the pretext of having less of an environmental impact, but in reality, it had more to do with gaining higher revenues for tour operators (Grenier 2007). In addition, vessels with overnight accommodations provided a solution to the lack of infrastructure and services on land (Watkins and Oxford 2008). In the 1980s, a more economical, land-based tourism (i.e., day tours, rather than overnight tours, small hotels, and hostels) began to flourish as tourists from different socioeconomic classes started visiting the archipelago; the overnight boat tour model simultaneously continued to develop throughout this decade (Grenier 2007). In the early 1990s, alleged concerns about rapid population growth caused by the expansion of land-based tourism led to an attempt to return exclusively to the overnight boat tour model. What resulted was what Grenier (2007) refers to as “selective tourism” that favors first-class accommodations, often provided by local and overseas tour operators offering overnight tours. With the 1998 enactment of the Special Law, which guaranteed a larger percentage of tourism revenues would remain in the islands; land-based tourism experienced a revival in the early years of the new millennium. More hotels and agencies were created and both land- and sea-based tourism continued to grow (Grenier 2007). In the future, different types of tourism will have different social, economic, and environmental impacts on the Galapagos.

Tourism is a human activity involving multi-scale phenomena that produce multi-scale patterns of impact (Baggio 2008). These impacts are driven at different scales by individual tourists, industries, and communities interacting upon geographical, economic, and ecological conditions. The macroscopic patterns generate feedback processes that, in turn, affect the interaction of tourists, tourism markets, the environment, and local populations. Examples of feedback effects include evolving markets, competition among tourist sites, changes in the attractiveness of tourist sites, and ecological deterioration. Feedback processes play an important role in driving development and bringing about social and ecological changes that produce inherently complex behaviors (Pizzitutti and Mena 2011, unpublished report).

This work in progress is the construction of *GalaSim*, an ABM simulation to capture decision-making at the very basic unit, that is, the individual tourist at different stages of the travel experience. The tourist chooses from a portfolio of opportunities, in some cases, long before the trip actually starts. These decisions are based upon the characteristics of the trip and the destination but are also based on the interests and socioeconomic characteristics of the tourist. Tourists are parameterized

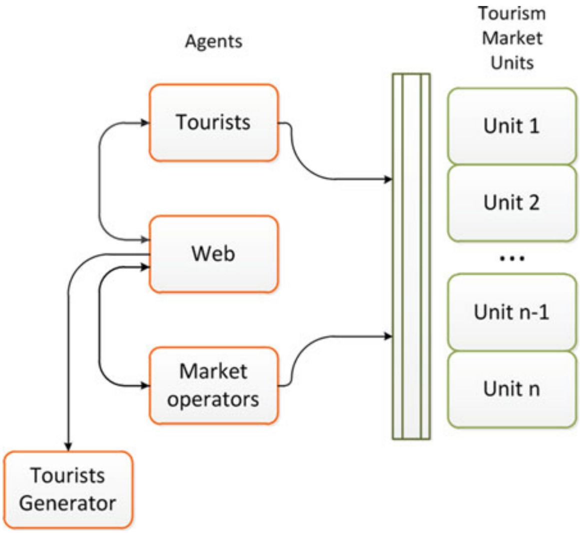

Fig. 3.4 Diagram of the *GalaSim* model (Pizzitutti and Mena 2011, unpublished report)

using characteristics collected by the official registry system of the Galapagos National Park. The model also aims to capture current local tourism infrastructure and markets and, in the future, implications to the local economy and environment. It is important to note that the use of an ABM to model tourism has been very limited (Cecchini and Trunfio 2007; Johnson and Sieber 2011), mainly due to the lack of information about tourism systems. In Galapagos, the rich collection of data about tourism and tourism infrastructure is important for the development of this kind of model.

In the first part of this tourism study, the model captures the interactions between tourists and tourism market operators in the Galapagos. In this model, market operators and tourists interact through a "virtual" platform, such as the Internet, that represents the interaction space for negotiating (a) the sale promotion, (b) the sharing of information about products, and (c) the purchase of many of the tourists' selections. This virtual platform can be viewed as a place for the storage of structured knowledge that permits tourists and market operators to engage each other and for the tourist to make trip selections and even trip preparations. The tourism market is represented as units that correspond to the tourism offerings and that can be viewed as a cell where tourists are allocated (Pizzitutti and Mena 2011, unpublished report).

Tourists enter into the system at rates corresponding to the official statistics of the Galapagos National Park and are created by a tourist generator agent, following a psychographic distribution (Plog 2001), and other distribution curves that describe demography, awareness, preferences, and budget (Pizzitutti and Mena 2011, unpublished report) (Fig. 3.4). The model uses a matrix of priorities based on endogenous characteristics and preferences. Tourists then choose market units, distributed across Santa Cruz, San Cristobal, and Isabela islands. Important agents are market operators who have the capacity to organize tourist agents. Market operators differ in terms of knowledge, access to information, efficiency, quality of products, and money to invest in tourism and their services. Tourist agents who choose vessel- and land-based modes are treated separately. The aim is to understand future trends of mobility within the archipelago and, eventually, the ecological and economic implications of tourism in the islands on human–environment interactions and the generation of income, wealth, and assets.

Climate Change as an Agent of Change

In the above ABM models, climate change is examined indirectly by creating linked relationships between the spread of invasive species and the choice of household livelihoods in agriculture, fisheries, and tourism. Climate models for the Eastern Pacific generally indicate that El Niño events will likely increase in frequency and magnitude for the Galapagos Islands. As such, ABMs can be used to model their impacts as social–ecological shocks to the social, terrestrial, and marine subsystems of the Galapagos.

In the Galapagos, the opposite extremes of ENSO, El Niño, and La Niña events have strong and contrasting implications for the stability of native ecosystems (Bliemsrieder 1998), the spread of invasive species (Tye and Aldaz 1999), and human livelihoods (Cruz 1985; Robalino et al. 1985). El Niño and La Niña events and their effects on terrestrial ecosystems are relatively well studied (e.g., Holmgren et al. 2001), although many uncertainties remain, mostly related to spatial and temporal lags. In the Galapagos Islands, reports of the effects of El Niño date back to the early 1950s, but the events that occurred in 1982–1983 and 1997–1998 have been well described, dealing mostly with the effects on endemic populations of flora and fauna.

The increase in rainfall associated with El Niño in Western South America has been identified as an important trigger for seed germination and germination blooms (Arntz and Fahrbach 1996). There are indications, however, that herbs are more sensitive than shrubs (Jaksic 2001) and that the effects differ over small spatial scales that increase patchiness in primary production (Gutiérrez and Meserve 2003; Jaksic 2001). In the Galapagos, reports indicate that the elevated rainfall rates and totals increase woody tree mortality, especially in dry areas; support the spread of selected invasive species; and promote the expansion of existing lianas and grasslands (Hamann 1985; Luong and Toro 1985; Itow 2003). Increased rainfall increases primary productivity by first promoting the germination of dormant seeds that later are consumed and spread by herbivores. Reports indicate that El Niño contributes to the appearance and spread of invasive species (Tye and Aldaz 1999). The link between herbivores and the spread of guava also appears to be quite strong, as seeds are dispersed by cattle, horses, pigs, birds, and rats (Ellshoff et al. 1995; GISD 2005) that eat the fruits and excrete the numerous seeds.

El Niño also affects the livelihoods of humans in the Galapagos. Reports point out the important decrease in fishing stocks (Robalino et al. 1985) and the negative effect on agricultural activities, including flooding pastures, destruction of cash and subsistence crops, diseases in cattle, and impacts to the infrastructure (Cruz 1985; Robalino et al. 1985). Fishermen and farmers must adapt to the changing environment, and in the case of El Niño, they must adapt to cope with this exogenous shock as there are strong feedbacks between land use intensity, land abandonment, and the effects of El Niño.

Conflicts between resource conservation and economic development in the Galapagos Islands occur as a consequence of a burgeoning human migrant population, primarily from the mainland of Ecuador and from tourists who visit the archipelago from around the world. This growing human population is now threatening the future of this ecologically fragile area. Due to this, in April 2007, the United Nations designated the Galapagos Islands "at risk" from the threats associated with population growth and economic development. Similarly, the Ecuadorian government declared an "ecological emergency" in the world-renowned Galapagos National Park and Marine Reserve.

One of the greatest threats to the ecosystems of the Galapagos Islands is the growing number, severity, and areal expansion of exotic plant and animal species (Tye et al. 2002; Tye 2006). Increased human presence has hastened the introduction of invasive species that are now so prevalent and severe that they threaten the native and endemic flora and fauna of the islands, ecosystem services, and the human–natural system. Thirty-seven of more than 800 alien plant species are considered highly invasive in the Galapagos Archipelago (Tye et al. 2002). Relative to the number of species they endanger, exotic species are the least studied threat to biodiversity (Lawler et al. 2006).

Measuring Landscape Dynamics

While ABMs are capable of spatially simulating shifts in human behavior and the adaptive resilience of social and ecological systems to environmental change, it is important to characterize initial conditions for the onset of the model and to correctly represent the composition and spatial pattern of land use/land cover for the study area, as well as the social and ecological landscapes that are fused together through an *Island Biocomplexity* context.

While information exists on all tourists and temporary workers who enter the Galapagos, a separate system tracks the entries and exits of all permanent and temporary residents. Ecuadorian census data were collected for 1990, 1998, 2001, 2006, and 2010, and a Living Standards survey was conducted for the islands in 2009 that provides detailed information on a wide variety of economic activities. These data are critical for establishing many of the rules and relationships used in ABMs, particularly, the geo-location of dwelling units, census units, demographic characteristics, roads, land parcels, and associated information that is used to characterize social dimensions in the islands. Conversely, satellite systems have been increasingly relied upon to gather space-time information on the environment, particularly land use/land cover change, as well as sea surface temperatures and the chlorophyll content of the marine environment. We have implemented strategies that involve the fused use of high spatial resolution data (e.g., WorldView-2, QuickBird, Ikonos, or ADAR digital aircraft data) fused with moderate resolution imagery (e.g., ASTER, Landsat), as well as coarse-grained systems such as MODIS imagery. In addition, we have fused optical systems with non-optical radar systems for landscape characterization.

In addition, analyses have been conducted that use multispectral satellite data such as Landsat (e.g., Joshi et al. 2006; Huang and Zhang 2007) and Advanced Land Imager data (ALI) (e.g., Stitt et al. 2006) versus the use of hyper-spectral data such as Hyperion (e.g., Asner et al. 2006; Pengra et al. 2007; Underwood et al. 2007; Walsh et al. 2008), and hyper-spectral digital aircraft data (e.g., Underwood et al. 2003; Miao et al. 2006; Hunt and Parker-Williams 2006) for characterizing land use/land cover change patterns. For Isabela, for instance, aerial photography was collected in 1959/1960, 1982–1985, 1992, and 2007. The imagery is maintained by the Ecuadorian Geographic Military Institute (IGM) for all of the Galapagos Islands. The March 2007 mission characterized the landscape of the Galapagos Islands at a scale of 1:30,000, in natural color, and with standard forward- and side-lap for stereoscopic viewing.

The general design is to acquire historical aerial photography and spatial-, temporal-, and spectral-resolution satellite data to construct a trend analysis of land use/land cover change and plant invasions. It is common to fuse multiple data sets, such as hyper-spectral Hyperion and multispectral Advanced Land Imager data. Historical to contemporary satellite imagery—including Landsat Thematic Mapper, Landsat Multispectral Scanner, and ASTER—as well as the 2007 natural color aerial photography of the Galapagos Islands and earlier aerial photo mission data are used as well. The temporal coherence of the imagery across the various sensor systems and image dates can be maintained.

A processing template can be developed that includes a consistently applied set of image preprocessing operations to spectrally, geometrically, and radiometrically correct images from each sensor system and time series. Preliminary steps often include the generation of a consistent set of vegetation indices (e.g., Normalized Difference Vegetation Index, Soil Adjusted Vegetation Index, Fractional Cover Index) and the Tasseled Cap Wetness-Greenness-Brightness transforms to extend the feature sets for image classification. Primary analyses can be based on pixel-based approaches (e.g., unsupervised, supervised) and object-based image analyses (OBIA) approaches to characterize the landscape into general land use/land cover types, with special emphasis on mapping forest (degraded and otherwise), grasslands, cropland, pasture, bare soil, and invasive species. Walsh et al. (2008) examined the use of multispectral QuickBird data and hyper-spectral Hyperion data to characterize guava for a test area on Isabela Island. Findings indicate a positive synergism between the different types of data and different image-processing methods (i.e., linear vs. nonlinear spectral unmixing and pixel vs. object-based image analysis) to characterize the environment.

Conclusions

Operating within an *Island Biocomplexity* context, we advocate a framework and perspective that is capable of addressing the linked effects of social–ecological systems in the Galapagos Islands. *Island Biocomplexity* maintains an adaptive resilience of local factors and distal forces that function through the coevolution of human–environment interactions to understand complex island ecosystems (Michener et al. 2002). Further, we demonstrate how an agent-based model can be developed to examine various scenarios of change to the social, terrestrial, and marine subsystems of the Galapagos Islands by fusing social and ecological information from social surveys and a satellite time series to develop rules and relationships, and a rich process understanding, of complex and dynamic systems in the Galapagos Islands and beyond.

The use of *Island Biocomplexity*, or complexity theory, within island settings offers a great potential for understanding coupled human–environmental systems, mainly through the generation of input and output parameters, such as flows of people, material, and capital. This is true in the Galapagos Islands, where relatively good information exists to describe the social and environmental domains. Additionally, ABMs and other methodological tools based on complexity explicitly embrace uncertainty as part of the system that is key for environmental management in island ecosystems, where small variations in key variables can change the trajectories and conditions of entire social–ecological systems.

Here, we have described work we are conducting using the Galapagos Islands as a natural laboratory. These examples illustrate a range of ABM applications from agriculture to tourism that can create future scenarios relevant to policy. Although complex systems research, including ABMs, is expanding quickly in the social and natural sciences, the methods are still experimental, and applications to public policy making are relatively few in number. The Galapagos Paradox can be tested using complex systems, but models can only inform about possible future scenarios and operative pattern–process relations. It is human agency that must protect this very charismatic and amazing place. *Island Biocomplexity* and complex adaptive systems are new frameworks and perspectives to assess the challenges of the Galapagos Islands and to present plausible alternative futures to protect and preserve this magical place.

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