Chapter 16
A Pragmatic Approach to the Management of Plant Invasions in Galapagos

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Abstract This chapter presents an overview of the process undertaken to understand alien plant invasions and work towards their effective management in the Galapagos Islands. Galapagos is a unique case study for the management of alien plants in protected areas because much the archipelago has few alien plants and the original ecosystems are relatively intact. We discuss a pragmatic approach developed over 15 years to help prioritise management of 871 plant species introduced to the islands. This approach includes understanding invasion pathways; identifying which species are present and their distribution; determining invasive species impact on biodiversity, ecosystem function and mutualisms;

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prioritising management using weed risk assessment; guidelines to prevent further introduction through quarantine and early intervention; and developing methods to control or eradicate priority species. Principal barriers to application of the approach are limited capacity and coordination among managers and inherent difficulties arising from invasive species traits such as seed banks and dispersal and their interactions with ecosystems. We also discuss the approach of managing invasive species individually and suggest it may be more appropriate, when feasible, for the relatively intact uninhabited islands and dry regions of Galapagos. The more degraded highlands of the inhabited islands need a more complex approach that balances costs with prioritised outcomes for biodiversity and ecosystem functionality.

Keywords Impacts • Islands • Ecosystem function • Mutualisms • Weed risk assessment • Priorities • Quarantine • Eradication

16.1 Introduction

The Galapagos Islands are a special case for the management of alien plants in protected areas. The majority of the land area – on the uninhabited islands – contains very few alien plant species and is in relatively pristine condition (Bensted-Smith et al. 2002). However, the core areas of human impact – on the four islands inhabited by humans – contain more introduced than native plant species and ecosystems are highly altered from their historical state (Snell et al. 2002a). Thus most of this chapter focuses on the 4 % of the Galapagos archipelago which has been colonised by humans and the parts of the protected area immediately surrounding these nuclei.

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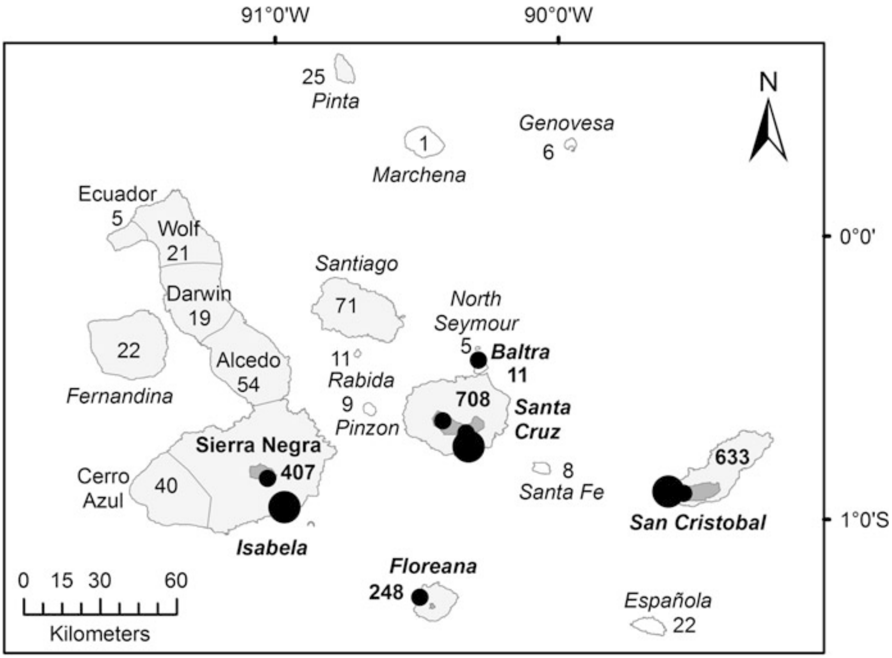

Fig. 16.1 The number of alien plant species on each island larger than 150 ha (with the six Isabela volcanoes shown separately because they are mostly ecologically isolated by bare lava on the lower flanks). Islands with a humid highland zone are *shaded light grey*. Currently inhabited islands are labelled in *bold*, with the inhabited area *shaded dark grey*; all remaining land areas constitute the Galapagos National Park. Towns and villages are shown as …. *black dots*. (Plant data from Charles Darwin Foundation Collections Database (CDF 2009) and Trueman et al. (2010); island names from Snell et al. (1996))

Eighty of the 871 non-native vascular plant species[1] recorded in Galapagos (up to year 2012) are found on the 46 islands and islets that have never been colonised. Figure 16.1 shows that the inhabited islands/volcanoes have an order of magnitude more alien plant species compared to the uninhabited ones. Most of the species on the uninhabited islands are herbaceous, annual or short lived perennials, probably accidentally introduced and unlikely to cause great impact (e.g. *Porophyllum ruderale*, ruda gallinazo). In contrast, all of the 871 species are found on at least one of the four main islands inhabited by people: Santa Cruz, San Cristóbal, Isabela and Floreana. Between 21 and 100 % of the humid highlands on these islands have been degraded through agriculture and alien plant and animal invasion (Watson et al. 2009), which effectively forms degraded nuclei surrounded

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[1] We have used species as the taxonomic unit throughout this chapter for consistency, but the 871 'species' in Galapagos actually include subspecies. In this chapter taxonomy and common names follows Jaramillo and Guézou (2012).

by less degraded dry peripheries. Baltra, the other colonised island, is an exception by having few alien species, due to being a small, low island without a humid zone. Many plant species introduced to the areas used by humans have spread into the neighbouring Galapagos National Park (GNP), including some that have been transmitted to uninhabited islands.

In the mid-1990s the Charles Darwin Research Station started a systematic process to catalogue, understand and prioritise invasive plant management, and over the last 15 years the authors of this chapter, and many others, have worked together to develop a pragmatic approach to managing plant invasions in Galapagos. The goal has always been to facilitate realistic management decisions that produce achievable and valuable outcomes. The development of this process was accelerated between 2002 and 2007 by the Global Environment Facility (GEF) funded project entitled "Control of Invasive Species in the Galapagos Archipelago". This ambitious programme had a number of elements including: baseline inventories, quarantine development, research on invasions, experimental eradications, awareness and participation programmes, capacity building, and development of a Galapagos-wide planning and policy framework. Whilst the consolidation of the results continues to this day, the legacy from this project is significant.

This chapter aims to outline the pragmatic management process as applied in Galapagos under three main umbrellas: (i) Understanding the problem (identify introduction and invasion pathways; identify what species are present and their spatial/temporal extent; determine their impact on biodiversity, ecosystem function and mutualisms); (ii) Developing management tools (prioritise species for management and border biosecurity; develop methods to control or eradicate priority species); and (iii) Addressing the challenges of applying our approach to attain achievable goals (the relative benefits of managing single species versus whole ecosystems for different parts of Galapagos; the importance of engaging people and the differing visions of various stakeholders). We use examples to illustrate each step of the management process and discuss limitations. We finish with a summary of lessons learned and an outline of management opportunities that are specific to the unique case of Galapagos.

16.2 Understanding the Problem

16.2.1 Plant Introductions and Invasion Pathways

Alien plants have likely been introduced to Galapagos ever since its discovery in 1535 when the archipelago was first opened up to humans. Early visitors included buccaneers, whalers and fishermen. Few introductions would have occurred prior to human settlement of the islands which began in 1807 and led to permanent human presence since 1879 (Grenier 2007). On his visit to Galapagos in 1835, Charles Darwin recorded 17 alien species in Floreana (a colony that was repeatedly

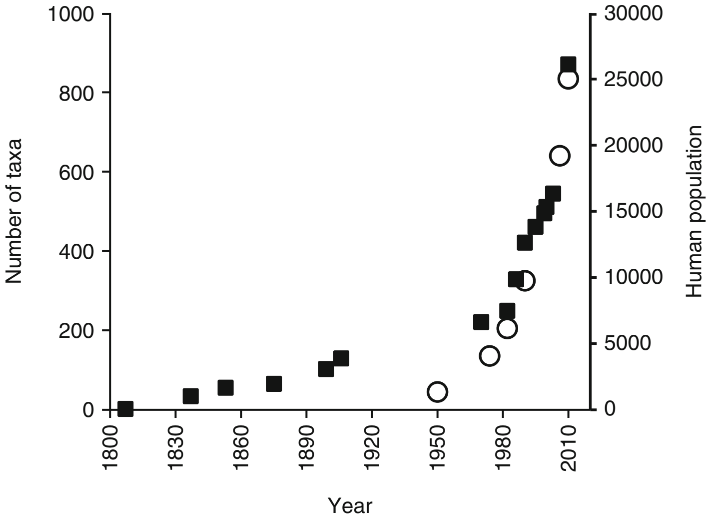

Fig. 16.2 Cumulative number of alien plant taxa recorded (*black squares*) and human population (*open circles*) in Galapagos since settlement in 1807 (Sources: alien species (Jaramillo and Guézou 2012; Tye 2006); human population (Grenier 2007; INEC 2007, 2011))

abandoned), all of which had been deliberately introduced for agriculture (Hooker 1851). Tortoise hunters had vegetable gardens on Santa Cruz in the nineteenth century, before that island was permanently colonised in the early 1900s (Lundh 2006).

In 2011, the alien flora of Galapagos amounted to 871 species (Jaramillo and Guézou 2012). Most of these were introduced in the past 30–50 years (Fig. 16.2; Tye 2006; Trueman et al. 2010). The recordings of alien plant species in Galapagos has increased exponentially or multi-stage linearly since records began in 1807, partly reflecting the introduction rate, but more importantly illustrating the changes in species recording method and effort (Tye 2006). Many species may have been present for years, even decades, before they were first recorded hence biasing rate of increase (Tye 2006). There is further uncertainty about the total number of aliens, because approximately 60 species are classified as questionably native, which pending further evidence could be native or introduced. Using fossil pollen and other plant remains, van Leeuwen et al. (2008) and Coffey et al. (2011) showed that nine species classified as questionably native or definitely alien had actually been present in Galapagos before humans. Nevertheless, anthropogenic introductions far outweigh the natural introduction rate by a factor of at least 13,000 (Tye 2006).

The impact of invasive plants on the Galapagos biota has been emphasised only since the 1970s (Schofield 1973), though the first invasions probably began prior to permanent human settlement. Examples include *Citrus* spp. that were introduced as anti-scorbutics by visiting pirates or whalers (Lundh 2006) and still persist in the wild today, and *Furcraea hexapetala* (Cuban hemp, cabuya) which was planted to mark a trail and had naturalised on Santa Cruz Island by 1905 (Lundh 2006).

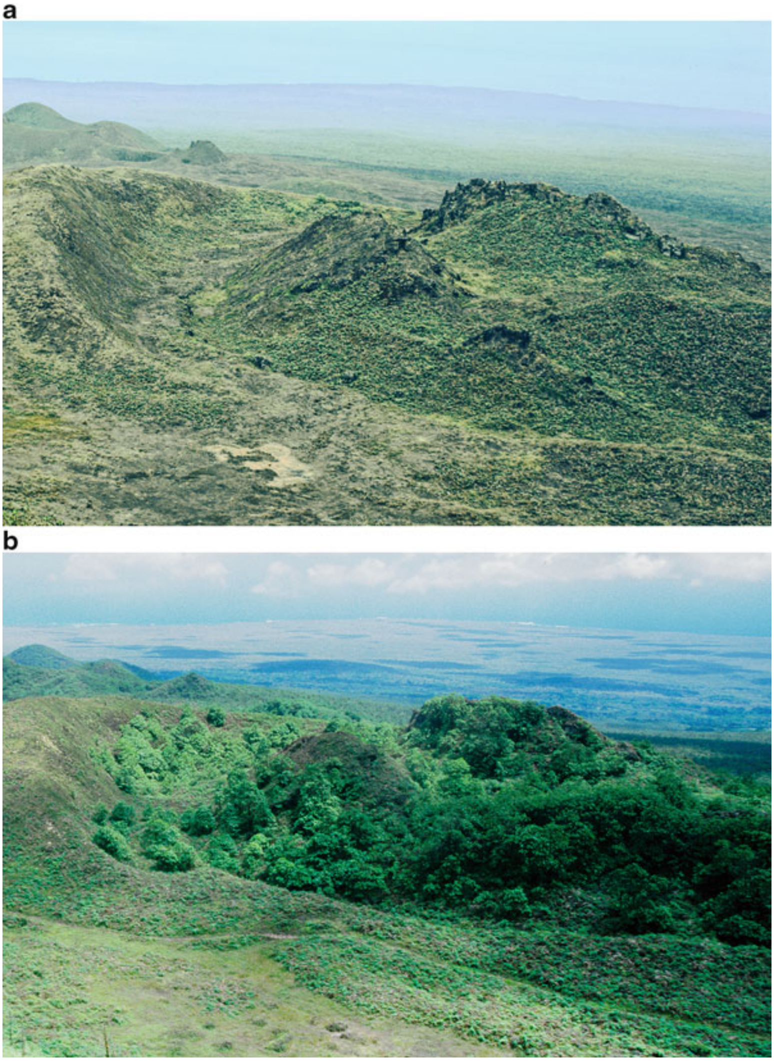

Fig. 16.3 Many parts of the highland grass and fern zone within the Galapagos National Park on Santa Cruz Island (**a** – 1970) have been invaded by the tree *Cinchona pubescens* (**b** – 2004) (Photographs by Frank J. Sulloway, taken looking east from Cerro Crocker, reproduced with permission from the photographer)

Widespread plant invasions and ecosystem transformation did not begin until well after settlement, and were facilitated by agricultural clearing and seed dispersal. One example is *Syzygium jambos* (rose-apple) that started to form thickets in San Cristóbal in the 1950s (Lundh 2006). On Santa Cruz the tree *Cinchona pubescens* (red quinine) began to spread widely in the 1970s (Hamann 1974; Fig. 16.3) and several other plant invasions accelerated after the 1983 El Niño

Fig. 16.4 Forest of the native *Scalesia pedunculata* (lechoso; young stand) and *Psidium galapageium* (guayabillo; with the brown epiphytic liverworts) (**a** – in 1975) has been replaced by taller forest of *Cedrela odorata* with a mid-storey of *Psidium guajava* (**b** – in 2004). Both photographs are from a permanent quadrat in the 'caseta' area in the Tortoise Reserve, Santa Cruz Island (Photographs by Ole Hamann, reproduced with permission from the photographer)

event (e.g. *Psidium guajava*, guava; *Rubus niveus*, blackberry; *Cedrela odorata*, Cuban cedar; *Cestrum auriculatum*, sauco; Fig. 16.4). In the south of Isabela, *P. guajava* now forms a monoculture of cover over 40,000 ha (Laura Brewington, personal communication, 2009) and was probably dispersed by feral cattle and established after a big fire in the 1980s.

Table 16.1 Current transformer species (those that change the character, condition, form or nature of ecosystems over a substantial area) and their biological characteristics

Family	Species	Habit	Dispersal	Evidence of seedbank in Galapagos/vegetative reproduction
Agavaceae	*Furcraea hexapetala*	Herb	Wind	Yes/yes
Boraginaceae	*Cordia alliodora*	Tree	Wind	Unknown/no
Commelinaceae	*Tradescantia fluminensis*	Herb	Animal[a]	Yes/yes
Crassulaceae	*Bryophyllum pinnatum*	Herb	Wind/vegetative fragments	Unknown/yes
Lauraceae	*Persea americana*	Hree	Animal[a]	No/no
Meliaceae	*Cedrela odorata*	Tree	Wind	No/no
Mimosaceae	*Leucaena leucocephala*	Small tree	Water, soil	Yes/no
Myrtaceae	*Syzygium jambos*	Tree	Water/animal	No/yes
Myrtaceae	*Psidium guajava*	Small tree	Animal[a]	Unknown/no
Passifloraceae	*Passiflora edulis*	Climber	Animal[a]	No/no
Poaceae	*Melinis minutiflora*	Grass	Animal[a]/wind	Yes/yes
Poaceae	*Panicum maximum*	Grass	Animal[a]	Unknown/yes
Poaceae	*Pennisetum purpureum*	Grass	Animal[a]	Yes/yes
Poaceae	*Urochloa decumbens*	Grass	Animal[a]/wind	Yes/yes
Rosaceae	*Rubus niveus*	Shrub	Animal[a], soil	Yes[b]/yes
Rubiaceae	*Cinchona pubescens*	Tree	Wind[a]	Yes[b]/yes
Solanaceae	*Cestrum auriculatum*	Small tree	Animal[a]	Yes/no
Verbenaceae	*Lantana camara*	Shrub	Animal[a]	Yes/yes

[a] Animal dispersal data from Blake et al. (2012), Connett et al. (in press), Guerrero and Tye (2011), Heleno et al. (2011, 2013b); and references therein)

[b] Seedbank data from Landazuri (2002) and Rentería (2002); All other data from author observations

To help understand the problem of alien plants in any place it is important to know how far the flora has progressed along the invasion continuum (Richardson et al. 2000); this can be done by determining which introduced species fall into each of the categories of naturalised, invasive and transforming. Of the alien flora in Galapagos, 332 species (38 %) are naturalised (Jaramillo and Guézou 2012) and 32 of these species (4 % of total) are considered invasive (Tye 2001). Table 16.1 shows a subset of 18 of these invasive species that are widespread and considered to be problematic for native ecosystems; these fit the bill of transformer species (sensu Richardson et al. 2000; Pyšek et al. 2004). They are all perennial, have effective dispersal mechanisms and mostly have a seedbank and/or vegetative reproduction (Table 16.1). This overall measure of progression along the invasion continuum is difficult to compare with other locations because of differences in sampling effort and methods, and differences in the definition of ‘invasive’ (Guézou et al. 2010). However the outnumbering of native flora by alien flora is similar to other oceanic islands, while the proportion naturalised and invasive is lower than on other oceanic islands (Trueman et al. 2010). Thus Galapagos is at an early stage of the invasion process (Tye 2006; Trueman et al. 2010). Even if no more introductions occur, some of the species already present will become naturalised and turn into transformers that impact native ecosystems.

Different types of plants have been introduced over various periods of human colonisation and this has influenced patterns of invasion and impact. Initially, intentional introductions were focused on useful, cultivated plants to be grown in the humid agricultural regions, while the focus has shifted more recently towards ornamental plants, grown mainly in gardens in the lowland urban areas (Tye 2006), which now form the majority of alien plant species in Galapagos (Atkinson et al. 2010). Many species have recently been recorded for the first time and although they may have been introduced much earlier, most of them still have a very limited distribution on private properties (Guézou et al. 2010; Trueman et al. 2010). A similar number of alien species are now grown in the urban areas of the dry lowlands compared with the rural humid highlands areas of Galapagos, although the most common species in each area are different (Trueman 2008; Guézou et al. 2010). Due to their mesic climate and earlier introduction history, the humid highland areas have suffered more invasions so far (Snell et al. 2002a; Watson et al. 2009). Invasions of ornamental species in the dry coastal towns have only recently begun. For example, *Kalanchoe tubiflora* (= *Bryophyllum delagoense*, chandelier plant) is now naturalising and dispersing into the adjacent GNP. The variability of the Galapagos climate also affects invasions. In particular, wetter periods associated with El Niño assist the establishment and spread of alien species in the islands (Hamann 1985; Luong and Toro 1985; Aldaz and Tye 1999; Tye and Aldaz 1999). Also, *Leucaena trichodes* (wild tamarind) persisted in gardens for many years, until a recent run of wet years enabled it to naturalise and establish a seed bank (R. Atkinson, personal observation, 2009). There is concern that a future warmer, wetter climate would favour further invasions in the dry lowland areas which occupy the majority of Galapagos land area and contain most of the endemic species (Trueman and d’Ozouville 2010).

16.2.2 Inventories: Baseline Data for Early Detection

To understand and manage alien plants we need to know what they are, where they are, whether they pose a problem, and which management options might be suitable. Exclusion and rapid response to incursions are widely considered to be the most viable, cost effective means of managing invasive species (Panetta and Timmins 2004), yet detailed distribution information is needed in order to carry these out. This information can be obtained by carrying out surveys of alien species (Hosking et al. 2004). A particular concern in Galapagos is the spread of alien species from the inhabited zones (private properties) into the GNP, so the inhabited areas have been the target for such inventories.

Between 2002 and 2007 a team of botanists carried out one of the most extensive surveys of alien species in any Pacific archipelago, visiting 6,031 private properties (97 % of the total in urban and rural zones) in the islands of Floreana, Santa Cruz, San Cristóbal and Southern Isabela (Guézou et al. 2010). The survey of 253 km^2 cost US$300,000 and 17 person-years of trained botanists' time (Guézou et al. 2010).

The survey results constitute a useful tool for management. Almost all species are represented by specimens in the Charles Darwin Research Station herbarium (CDS). With few exceptions each species record is assigned to a particular property. Most species were uncommon, with 252 species recorded in five properties or less (Trueman et al. 2010). If a decision were made to attempt to manage some uncommon but potentially invasive species in the future, the inventory data could be used to select potential targets and guide more detailed surveys.

This inventory was also an excellent community outreach tool, and was well received as evidenced by the small percentage of properties where entry was refused (<1 %). The team met with landowners and discussed invasive plant problems, thus increasing community awareness. All species detected were subsequently evaluated by the Galapagos Weed Risk Assessment which is discussed further below.

16.2.3 Impacts on Biodiversity and Ecosystem Function

There is little hard evidence that invasive plant species cause extinctions (Gurevitch and Padilla 2004). However, there is much evidence that they cause changes in ecosystem structure and function, and an understanding of such impacts can be used to determine whether changes are reversible and to inform management.

Cinchona pubescens and *R. niveus* are the two best studied transformer species (sensu Pyšek et al. 2004) in Galapagos; there is quantitative information on their biotic and abiotic impacts. Both species were introduced to the highlands of Santa Cruz Island, *C. pubescens* in the 1940s, now covering over 11,000 ha (Buddenhagen et al. 2004), and *R. niveus* in the 1960s (Lawesson and Ortiz 1990), now covering more than 30,000 ha on five islands. *Cinchona pubescens* is converting formerly treeless vegetation zones into forests, and *R. niveus* has formed dense impenetrable thickets up to 4 m high.

A 7-year study showed that *C. pubescens* significantly reduced species diversity and the cover of most species by at least 50 % in the invaded area. Endemic herbaceous species were more adversely affected than non-endemic native species (Jäger et al. 2009). Despite the fact that no species went locally extinct throughout this period where *C. pubescens* cover averaged 20 %, species did disappear when *C. pubescens* cover reached 100 % (Jäger et al. 2007). Similarly *R. niveus* had adverse impacts on the native plant community had it invaded (Rentería 2011;

Rentería et al. 2012a, b). Species richness was reduced by 56 % when *R. niveus* cover exceeded 60 %, with herbs being more affected than ferns. In addition, abundance of almost all species was significantly reduced in heavily invaded sites (>60 % *R. niveus* cover), compared with medium to low invaded sites (<60 % cover). Such studies provide a scientific basis for management intervention, although in these particular cases more information, such as social values of different elements of the invaded ecosystem, would further inform management.

Tradescantia fluminensis (wandering jew) is an example of a species that has fast become a transformer. It was first recorded in 1985, though apparently introduced in 1972 (Patricia Jaramillo, personal communication, 2012) from Loja in continental Ecuador as a ground-cover under coffee plantations (Anne Guézou, 2012). It was first observed to be invasive in 2005 around Los Gemelos (Rentería and Buddenhagen 2006), the most important remnant of *Scalesia pedunculata* forest, and is now widespread in the humid and transition zones on Santa Cruz Island (M. Gardener, M. Trueman, R. Atkinson, H. Jäger, A. Guézou, 2011). It spreads vegetatively and its seeds are dispersed long distances in the guts of giant tortoises (Blake et al. 2012) and birds (Heleno et al. 2013b). It forms a thick mat on the forest floor which inhibits recruitment of native herbaceous species (M. Gardener, personal observation, 2011). Although these observations and impacts have not been quantified in Galapagos, it is likely that this species is already causing reduced diversity and abundance in Galapagos as it has done in New Zealand (Standish et al. 2002).

In a meta-analysis, Vilà et al. (2011) showed that apart from changing biodiversity patterns, alien plant species often change ecosystem functions, including changed physical conditions which can act as irreversible barriers to restoration. In Galapagos, photosynthetically active radiation was reduced by 87 % under the *C. pubescens* canopy, while precipitation increased by 42 % because of enhanced fog interception (Jäger et al. 2009). In very dense *R. niveus* stands (>80 % cover), sunlight reaching the understory (0.5 m height) was reduced by 94 % whereas in medium to low invaded sites (<20 % cover), sunlight was reduced by 45 % (Rentería 2011). These altered abiotic conditions are expected to lead to alterations in both alien and native species composition and abundance, although in both these cases there is no reason to believe the changes are irreversible, as removal of the invader could eventually restore the original physical conditions.

Some of these impacts can be attributed to specific features of the invader. *Rubus niveus* showed faster growth rates and biomass production than four co-occurring native woody species and had a larger seed bank than native species in the invaded areas (Rentería 2011). Invasive species typically have faster growth than native species, and often also have higher specific leaf area (SLA; Daehler 2003). The latter is true for *C. pubescens*, which has a significantly higher SLA than the endemic dominant *Miconia robinsoniana* (Galapagos miconia) and the native *Pteridium arachnoideum* (bracken fern) that naturally occur in the invaded area, as well as a higher leaf turnover rate (Jäger et al. 2013). Total nitrogen, ammonium and phosphorus concentrations in soil were significantly higher in invaded compared to non-invaded areas in the Miconia zone (Jäger et al. 2013). Leaf litter from invaded areas also contained more phosphorus (Jäger et al. 2013). These results suggest that a greater cover of *C. pubescens* over *M. robinsoniana* and *P. arachnoideum* means more faster-decomposing leaves, accelerated nutrient cycling and thus increased nutrient availability in the soil (Jäger et al. 2013).

16.2.4 Impacts on Plant Reproductive Mutualisms

Plant animal mutualisms can be used as a measure of ecosystem functionality in invaded systems. Recent research in Galapagos has deepened our understanding of pollination and seed-dispersal and the role of alien plants (Buddenhagen and Jewell 2006; McMullen et al. 2008; Guerrero and Tye 2011; Heleno et al. 2011, 2013b; Chamorro et al. 2012). Many frugivorous animals, particularly birds but also reptiles, are trophic generalists which readily incorporate invasive plants into their diets and thus facilitate their spread (Bartuszevige and Gorchov 2006; Williams 2006). This makes containment difficult. In Galapagos, 12 bird and three reptile species were found to disperse seeds of alien plants (Heleno et al. 2013b). Whilst only 5 % of the total number of seeds where alien, they were present in 17 % of nearly 3,000 animal droppings and represented 24 % of all seed species. Although this suggests high usage of alien plants by frugivores, these values are still moderate when compared to relative abundance of alien plants in the Galapagos and values from other oceanic archipelagos such as Hawaii or the Azores (Chimera and Drake 2010; Heleno et al. 2013a). As in other oceanic islands, reptiles are important seed dispersers in Galapagos. The widespread lava lizards (*Microlophus* spp.) are known to disperse seeds of at least 27 species, including eight aliens (Heleno et al. 2013b) while the giant tortoises (*Chelonoidis nigra*) are known to disperse at least 48 species, including 16 aliens, over large distances (Blake et al. 2012).

Galapagos has few invasive birds, which may have limited the spread of invasive plants; however other alien vertebrates such as cattle, donkeys, rats and horses, and also native vertebrates, are contributing to their spread (Clark 1981; Fowler and Johnson 1985; Rentería and Buddenhagen 2006; Chimera and Drake 2010; Heleno et al. 2011, 2013b). The potential role of the alien bird, smooth billed ani (*Crotophaga ani*), in plant invasions is hard to evaluate, however Guerrero and Tye (2011) and Connett et al. (in press) show that it might be an important disperser of at least four invasive species including *R. niveus* and *Lantana camara* (lantana).

A community level assessment of the importance of native and introduced pollinators for both native and invasive plants is still in progress, but preliminary results suggest that while the invasive plants are predominantly affecting pollination networks on inhabited islands, introduced insects are changing species interactions patterns even on the most remote islands (Chamorro et al. 2012; Traveset et al. 2013; Traveset and Chamorro, unpublished data). The proportion of self-compatible species in the Galapagos flora, and evolutionary trends in this trait, are unclear (Tye and Francisco-Ortega 2011). The Galapagos native flora is characterised by small, drab–coloured flowers, with poor rewards and associated with a depauperate pollinator fauna (McMullen 2009; Chamorro et al. 2012). Tight co-evolution between plants and pollinators is likely to be rare in Galapagos, compared with older archipelagos, especially those with specialist bird pollinators, like Hawaii. Given the relatively recent human presence in Galapagos and the few documented extinctions, there is no reason to suspect that native plants are already threatened by limited pollination. However, this could change abruptly with extinction of a keystone pollinator species like the endemic carpenter bee (*Xylocopa darwini*) which is known to visit at least 84 plant species (McMullen 1989; Chamorro et al. 2012).

In conclusion, it is still too early to say if shifts in the assemblages of mutualists, either by direct introductions or as a consequence of vegetation shifts, will disrupt patterns of seed production and dispersal of insular plants in Galapagos. However accumulating evidence suggests that some of these disruptive processes might have already begun to occur.

16.3 Developing Management Tools

16.3.1 Weed Risk Assessment to Prioritise Management

A precautionary approach to alien plant species is especially warranted in Galapagos because 96 % of the land area is a national park which supports a world-renowned unique biodiversity. Correctly distinguishing potential invaders from non-invaders has been the main focus of weed risk assessment worldwide particularly for pre-border screening of potentially useful species (Gordon et al. 2008; Weber et al. 2009; Koop et al. 2012). While there is less pressure from new introductions in Galapagos at present, due to quarantine laws, some introductions do still occur.

With 871 alien plants already present in Galapagos and limited resources available, there is a need for a tool to prioritise management based on the risk of each species. An objective risk assessment system, using a modified Australian Weed Risk Assessment protocol (AWRA) (Pheloung et al. 1999; Daehler and Carino 2000; Gordon et al. 2008; Weber et al. 2009; Koop et al. 2012) was therefore developed, with a focus on assessment of already-introduced species. Of the 49 questions in the AWRA, a small subset are known to be most useful to predict invasiveness, i.e. questions that relate to climate match in home range, dispersal, the presence of a congeneric invader, evidence for invasiveness elsewhere, a positive response to disturbance, short maturation and ability to propagate vegetatively (Caley and Kuhnert 2006; Weber et al. 2009).

The Galapagos WRA (GWRA) has two parts (Tye, Buddenhagen and Mader, unpublished data): one to assess the potential invasiveness of a species that may be introduced to Galapagos (a screening function similar to the AWRA) and the other, which we focus on here, to describe or predict the invasiveness of plant species already present in Galapagos. Literature and internet resources provide answers to questions regarding behaviour of a species outside Galapagos, and local expert opinion provides information on behaviour in Galapagos. The answers contribute to a scoring system that allocates species into mutually exclusive categories based on definitions by Richardson et al. (2000) and Pyšek et al. (2004): (1). Transformer (e.g. *R. niveus*); (2). Naturalised likely transformer (e.g. *Piper peltatum*, Santa María); (3). Naturalised but no evidence for future invasive behaviour (i.e. it could become a transformer or integrator (e.g. *Kalanchoe tubiflora*); (4). Integrator - long established in Galapagos but believed to have low impact (e.g. *Plantago major*, greater plantain, or *Pseudelephantopus spicatus*, dogs tongue); (5). Not naturalised potential transformer (e.g. *Pueraria phaseoloides*, kudzu, or *Acacia nilotica*, Nile acacia); and (6). Not naturalised in Galapagos and not a known invader elsewhere (e.g. *Plumeria rubra*, frangipani).

Management options can then be considered for each species. One option is to do nothing: many alien plants appear to be largely harmless wherever they occur (Category 6). ‘Integrators’ (Category 4) would also not normally be a focus of management for conservation purposes. These are typically plants that have been naturalised in Galapagos for decades and have spread to, or had the opportunity to spread to, all suitable habitats but are still either clearly confined to areas of human disturbance or have low impact in natural areas (e.g. ephemeral, low density, small stature or low growth habit, and without other negative effects). Category 5 species are obvious targets for eradication to prevent potential future impacts. Most populations of transformers (Category 1) might be regarded as impossible to eradicate (if they are too widespread) although some rarer ones, or species likely to hybridise with endemic species, might be susceptible to eradication or worth subjecting to site-based control (to protect localised biodiversity of high value), or biocontrol or inter-island quarantine measures. Some preliminary results from the GWRA have been used to inform pilot eradication projects, though the full assessment has yet to be formally implemented in Galapagos. Once the results are communicated to management agencies, then appropriate management decisions can be made for each species.

16.3.2 Management Options

For a conservation manager, the ultimate goal of any action against invasive species should be the conservation or restoration of native species or ecosystems (Genovesi 2007). The hierarchical approach promoted by the Convention on Biological Diversity (CBD 2002) is a useful framework for invasive species management, based on the rationale that financial investment early on in the invasion process is more cost effective, and puts less strain on the natural system than controlling already established invasive species (McNeely 2001). Exclusion is the first goal, but if an incursion occurs, then early detection and timely eradication are crucial to prevent establishment. If these methods fail and the alien has established in the wild, options include containment, control, biocontrol and no action.

Prevention is by far the most important tool for managing invasion. In recognition of this the Quarantine Inspection System for Galapagos (QISG) began in 1999. In 2009 its function was incorporated into Agrocalidad – a national agency responsible for animal and plant health. The principle that all species are potentially invasive until proven otherwise, combined with a permitted species list, is the basis of the QISG. Inspectors are based at sea and air ports in continental Ecuador and in Galapagos. There are also strict quarantine rules and inspections for travel between islands, especially to uninhabited islands, which, for the most part are free of transformer species. When species that are not permitted are detected, they are identified and either lodged in reference collections or destroyed. Although the QISG has created a high level of consciousness about invasive species and may have slowed the importation of alien plants, an evaluation in 2007 found it to be largely ineffective because it was under-funded and under-staffed (Zapata 2007).

Eradication is the best alternative after prevention fails, before spread is significant. The GWRA was used to choose plant species for a pilot eradication programme in Galapagos. Thirty populations (where a population = one species on one island) were chosen for evaluation for eradication feasibility, based on three criteria: (i) limited distribution as known from inventories, field surveys, and interviews with landowners (e.g. Soria et al. 2002); (ii) proven behaviour as invasive elsewhere in the world with a climate similar to Galapagos (e.g. Buddenhagen 2006); or (iii) already invasive somewhere in Galapagos. Information was collected about the factors affecting feasibility of eradication and its cost, including among other things discussions with landowners. Twenty-one populations (18 species) reached management stage, the earliest in 1996. Four of the eradication operations were successful, all in Santa Cruz; *Rubus adenotrichus* (mora silvestre) and *R. megalococcus* (Sarsa mora; Buddenhagen 2006), *P. phaseoloides* (Tye 2007), and *Cenchrus pilosus* (abrojo). Each of these species covered less than 1 ha in net area and was on land with a single owner (Gardener et al. 2010b). It is likely that two more species, *Persea americana* (avocado) and *Sapindus saponaria* (soapberry), have been eradicated in Santiago: both these are trees with slow maturation times, no long-lived seed bank, and limited distributions. Most of the remaining projects were abandoned after 1 or 2 years of data collection, mainly because their extent was greater than initially thought, and because search and control costs were too high. In some cases, preventing long distance seed dispersal and managing a long-lived seed bank further hampered success, for example *R. niveus* (Rentería et al. 2012a). Another barrier to eradicating species with small distributions was a lack of permission from land-owners to remove plants (e.g. *A. nilotica* and *Cryptostegia grandiflora*, rubber vine). The Special Law for Galapagos (Congreso Nacional 1998) actually has provisions that allow government officials to enter private property for managing invasive species; however, unfortunately this provision, like many others, has not been enforced.

Containment is a component of eradication projects and also a management option in its own right. The requirements for containment are the reduction of long distance dispersal and the timely detection of new foci (Panetta and Cacho 2012). Because most invasive species in Galapagos are either wind or animal dispersed, the vectors of dispersal are difficult to manage, as is plant fecundity. As we can see from the *R. niveus* example above, these conditions may be impossible to meet when a plant is widely naturalised.

Control or maintenance management is controlling an invader at a density sufficiently low to produce the desired conservation outcome. Typical maintenance options include mechanical, chemical, and biological control (Simberloff 2003). In Galapagos, both manual and chemical controls are used and have been developed for various species (Gardener et al. 1999; Buddenhagen et al. 2004). Control, unlike eradication, is indefinite and, although it may not have a large initial cost, can become accumulatively expensive in the long-term. It is thus important to undertake control only where the conservation objective is achievable and where potential biodiversity or socio-economic losses are considered to be unacceptable if no management action is taken. This means that the target species should only be reduced to below a threshold of impact.

Local control is carried out by the Galapagos National Park Service (GNPS) in sites of high biodiversity value or importance for tourism. A recent evaluation of alien plant control projects in the GNP between 2005 and 2010 included 17 projects on five islands covering 11 species (García and Gardener 2012). Approximately US $3,350,000 were spent on these projects to manage a total area of nearly 2,000 ha at a cost of US$280 per ha per year. Control outcomes were varied: some, such as the control of the tree species *C. odorata* and *C. pubescens*, reduced densities to below a threshold of impact whereas others, such as control of *R. niveus*, were ineffective and the disturbance may have facilitated further invasion; a major constraint was rapid recolonisation from the seed bank or vegetative shoots (García and Gardener 2012).

Biological control of widespread invasive species has been used effectively for the last century, sometimes providing exceptional value for money. For example, a recent economic analysis has shown an overall benefit–cost ratio of 23:1 for biological weed control programmes in Australia (Paige and Lacey 2006). Van Driesche et al. (2010) reviewed weed biological control projects for protection of natural ecosystems worldwide and found that 60 % achieved useful levels of control. There are also inherent risks associated with biological control that can lead to unintended consequences, thus informed decision-making is critically important (Simberloff 2012). Biological control has been successfully implemented in Galapagos for the management of the invasive *Icerya purchasi* (cottony cushion scale) using a cardinal ladybird (*Rodolia cardinalis*; Calderón-Alvarez et al. 2012). This success led to interest for other projects including the development of biological control agents for *R. niveus* and *L. camara* (Rentería and Ellison 2007; Atkinson et al. 2009). If implemented, biological control for *R. niveus* would require a significant up-front investment and could take up to 10 years – the development of a control agent was quoted at USD$660,000 by the Centre for Agricultural Bioscience International (Mark Gardener, 2011) and does not include management and coordination costs. To put this in context, the cost of control action for *R. niveus* on a single island (Santiago) has been approximately USD $582,000 over 6 years (Rentería et al. 2012a).

16.4 Challenges of Applying Management

16.4.1 Managing Species or Ecosystems

All of the above methods are aimed at managing alien species individually. Legislation is also often prescriptive at species level (e.g. declared weeds), and management of single species is operationally easier to achieve. However, single weed management strategies can result in unwanted or unexpected negative outcomes at the community or ecosystem levels (Zavaleta et al. 2001). The most common of these unwanted outcomes is where an invasive species is reduced in density only to be replaced by another. For example, in Galapagos the disturbance created by control of *C. pubescens* may have facilitated invasion by *R. niveus* (Jäger and Kowarik 2010). The recognition that interactions among species are crucial to maintain ecosystem functioning (Duffy et al. 2007) has recently highlighted the importance of framing conservation efforts at the community level. This means including information on how species interact (Millennium Ecosystem Assessment 2005).

In Galapagos, where invasions have not drastically altered ecosystem processes, such as on uninhabited islands and to a lesser extent dry lowlands of inhabited islands, managing alien species individually is still a worthwhile approach. There is also a moral imperative to keep these areas as close to their pre-human state as possible. Galapagos still has 95 % of its original, pre-human biodiversity (Bensted-Smith et al. 2002) and relative to most other oceanic archipelagos is in good ecological order. In these areas, a suitable goal is “the restoration of the populations and distributions of all extant native biodiversity and of natural ecological/evolutionary processes to the conditions prior to human settlement” (Snell et al. 2002b). In these areas we therefore support a species-led approach focusing on eradication and containment of priority species.

However, on the inhabited islands, particularly in the humid highlands, ecosystems are highly degraded. There are so many different invasive species and ecological impacts that the removal of one species is likely to result in replacement by another invasive. Here, the pre-human state is not fully attainable given realistically available resources. Novel ecosystems, those that have new species combinations arising through either species invasions or environmental change, are widespread on continents and islands and often objects of conservation for their own sake (Chapin and Starfield 1997; Vitousek et al. 1997; Jackson and Hobbs 2009). Owen (1998) describes a site-led approach which is based on the biodiversity value of a site, level of disturbance, the risk of aliens, and the cost of management. A more sophisticated tool for the same approach is scenario planning, which uses social and biological data to model outcomes of different management strategies, assisting stakeholders to make informed decisions (Roura-Pascual et al. 2011; Hulme 2012). Such approaches may be more suitable for planning conservation in the more degraded ecosystems in Galapagos. The goal would be to maintain as much native biodiversity as possible, together with original functionality, and undertake management interventions that maximise benefits over the total area of intervention (Gardener et al. 2010a). Transformer species that directly impact biodiversity will still require drastic intervention to prevent biodiversity loss, and biocontrol may be an option for such species.

16.4.2 Involving People

Management of alien plants is a matter of societal choice: perceptions, values, motivations, desires and needs of people will determine if and how management goals are determined and attained. In Galapagos, various stakeholders are responsible for this management. The GNPS (national government) manages alien plants within the GNP. However, alien plant invasions in the GNP spread from the inhabited areas. The municipalities (local governments) are responsible for managing urban and agricultural lands but the provincial Governing Council and the Ministry of Agriculture (national government) also have important roles on these private lands. The prevention of new introductions comes under the remit of the QISG, which is part of Agrocalidad (another national government department). It is a challenge to have all these agencies working together for overall coordinated management of alien plants in the archipelago. Additionally, all of this top-down management can only be effective with community support. We expand on some of the challenges below, relating them to the various aspects of alien plant management discussed above.

Within the GNP, major challenges to successful management are limited technical capacity and scientific knowledge. The lack of scientific knowledge is compounded by the long history of poor information transfer from researchers to managers, including language barriers. In the past this has resulted in some conflict within and between stakeholder groups, or distrust from the community. As a result, an inter-institutional committee supported by a trust fund for the management of invasive species was established in 2011 to mitigate some of these problems. This has helped in some ways. For example, GNPS provided free herbicides and equipment for the control of invasive species on private land. Another issue is that private landowners rarely work together, so that even if one farmer controls invasions on his or her own land, reinvasion is highly likely from surrounding farms and the GNP.

The limitation in technical capacity is perhaps more concerning. Within GNP, there is no long-term institutional commitment to an adaptive, well designed invasive plant management strategy. For example, management goals (including eradication, control and biocontrol) are not chosen strategically and appropriate techniques are not employed. Working toward achievable objectives, tracking costs, documenting plans, results, and failures for any project that is implemented requires much discipline. This long-term vision needs to be part of the organisational culture if effective management is to be achieved. There is also a need for regular training and for monitoring, evaluation, and adaptive management.

Differences in values held by various sectors of the community can lead to conflicts when species that produce benefits to the community are also invasive. Examples are *C. odorata* and *C. pubescens* that are both valuable timber trees and also highly invasive in the GNP and the agricultural zone. Extraction of both trees is allowed under permit from the GNPS. Ironically, both species (which are native to Ecuador) are considered threatened by over harvesting in their native range. *Cedrela odorata* is listed by the IUCN as Vulnerable (IUCN 2011). There is pressure to develop a sustainable harvest of *C. odorata* in Galapagos, despite a GNPS campaign to control it in some parts of Santa Cruz.

Another challenge is changing values over time. Approximately 80 % of the alien plants species in Galapagos were introduced on purpose, for medicine, food, timber, forage, or ornamentation. Many of them are already invasive. Thus some species that were earlier regarded as successful cultivations are now considered serious pests. Other species may become invasive in the future and suffer the same change in value. An example is *Aristolochia elegans* (Dutchman's pipe) which is said to cure stomach problems; there are currently less than 20 plants on a single farm in Galapagos. However it is known to be invasive and problematic in Australia (Skoien and Csurhes 2009) and could potentially cause future problems in Galapagos. This would constitute an easy eradication target but permission was not given by the landholder because it is considered a useful (yet harmless) species. In this and other examples in Galapagos, it has sometimes proven difficult to explain the precautionary principle to the public.

One of the big challenges in Galapagos is the continual influx of people from the mainland, many of whom are not aware of the vulnerability of Galapagos ecosystems to their actions. Thus a continual awareness-raising and education approach is needed for all stakeholders to produce a community based vision and integrated action plan for invasive species management. The best example of a win-win solution so far in Galapagos has been with a native garden project – providing native species as alternatives to introduced ornamentals, thus reducing the future threat to the GNP and to agriculture on the islands (Atkinson et al. 2010). There has been a high level of community and local government support for the project which has raised awareness about the potential harm of alien plants, whilst also satisfying a social need for ornamental gardens.

16.5 Conclusion: Core Lessons Learnt

Research into alien plant issues in Galapagos has contributed greatly to our understanding of introductions, invasions, impacts and management options. Nine core lessons have emerged from this work over the last few decades and can provide valuable advice to other regions:

(i) Most plants were introduced to Galapagos in the last 50 years and appear to be still in the early stage of invasion. Even if no new introductions occur, the number of naturalised, invasive and transforming species will increase.
(ii) Detailed surveys focused on inhabited areas (the nuclei of plant introductions), and freely available results, form the cornerstone of effective weed management. Continuous monitoring is required to detect new introduced species and help to understand how naturalised species might be spreading.
(iii) Impacts of invasive plants are not fully understood. Where quantified, increasing invasive species cover was correlated with decreases in native diversity and abundance. Impacts were also observed on physical parameters such as light, water and nutrients. There is little understanding of ecosystem-level impacts and the dynamic nature of the invasions.
(iv) Our understanding of mutualistic networks in Galapagos and the impact of invasive plants on them is still limited. To date it appears that seed-dispersal and pollination networks are still not severely impacted but are changing.
(v) The Galapagos Weed Risk Assessment system can help prioritise the management of alien plant species.
(vi) A number of tools for prevention, eradication and control have been developed in Galapagos. Disciplined application of prevention and early intervention strategies should lead to successes with fewer resources. However, it is still common practice to try to manage species that are too widespread for cost-effective control.
(vii) In the more pristine areas of Galapagos, a species-led approach to invasive plant management is appropriate. In highly degraded areas, a more complex approach is needed to prioritise management spending at a site level to achieve optimal outcomes for biodiversity and ecosystem function.
(viii) Within institutions responsible for alien plant management, the main challenges to successful outcomes are the limitation in technical capacity and scientific knowledge, and lack of information transfer.
(ix) Local communities are central to weed management and must be fully involved in management planning and implementation.

As discussed throughout the chapter, most alien plants and their impacts are concentrated on the four inhabited islands, especially in the humid highlands. The more pristine uninhabited islands have been protected from plant introductions due to their remoteness. This remoteness has two forms. First, human visits to these uninhabited islands are very limited and highly regulated, so direct impacts are minimal. Second, the physical (insular) distance from the inhabited islands limits the dispersal of introduced plants. However, increased human traffic from tourism, conservation activities and illegal camps reduce remoteness and increase the probability of chance introductions. Furthermore, there are early signs that the insularity is decreasing. Research shows that introduced plants are dispersed by frugivores (Heleno et al. 2013a) and some of these may be capable of inter-island movement. For these reasons the management of the inhabited and fully protected islands must be integrated.

Galapagos is iconic in the conservation world and many people feel that if it is impossible to manage plant invasions there, then there is not much hope for the rest of the world. A number of opportunities exist in Galapagos that are not available in other protected areas: (i) Insular geography with limited pathways for further introductions; (ii) 96 % of the land area is protected; (iii) 95 % of known native species are still extant; (iv) Few invasive plants are established or widespread in the dry lowlands: preventative action here would be beneficial to biodiversity protection; (v) There is a relatively high level of awareness of invasive species, with supporting legislation; (vi) The small size of the human population presents the opportunity to further raise awareness among the majority of residents; (vii) Labour costs are relatively low, so management costs are not prohibitive; (viii) Few introduced vertebrates are established, resulting in limited seed dispersal; and (ix) Pollinator and disperser failure has not occurred in native plants yet.

Scientists, managers, governing agencies and the community need to work together to overcome barriers and make the most of these opportunities for effectively managing plant invasions. As in Hawaii, both conservation science and management must “focus on explicit planning that adequately reflects biological and fiscal realities, rather than impractical, unfocused, and unachievable wish lists” (Duffy and Kraus 2006). A shared, realistic vision and a pragmatic approach to achieve that vision will be essential for success in Galapagos.

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