Biological Invasions

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Introduction

The introduction of species and their naturalization is presently considered one of the important mechanisms responsible for global change, leading to profound alterations in ecosystem structure and function, homogenization of biota, reduction of biodiversity and to the extinction of species (Huenneke 1997, Williamson 1996, Lodge 1993, Vitousek 1990, Vitousek *et al*. 1987).

Biological invasions and species introductions have fascinated biologists for a long time. Darwin, in his 1859 book "On the origin of the species", alluded to the fact that some domesticated animals that were taken by navigators from Europe to America and Australia had multiplied very quickly, sometimes affecting the survival of native species.

A **biological invasion** occurs when an organism, of any kind, reaches a site beyond its former area of distribution, becomes established and spreads (Williamson 1996); that is, invasions occur when a species colonizes and persists in a new geographic area (Shigesada & Kawasaki 1997).

Some heterogeneity exists in the concept of invasive species. For instance, Usher (1991) suggested the following definitions: i) introduced species – transported intentionally or accidentally, by human action, to an area outside of its natural geographic range; ii) invasive species – introduced species that increases its numbers and distribution area in the new region, without human intervention.

However, natural biological invasions would be excluded from this scenario. Alternatively, it is possible to use the invasive species concept as a geographic criterion, simply meaning that a new region or habitat has been colonized; and, on the other hand, to establish the different phases of the invasion process (Richardson *et al.* 2000).

Other authors considered as invasive those alien species which colonized natural and semi-natural ecosystems (Cronk & Fuller 1995). This might be somewhat restrictive, since introduced species in a disturbed habitat might later establish in ecosystems not so affected by human action.

Furthermore, Rejmánek (1995) clearly separated the concepts of invasive, weed (pest) and colonizer. A **weed** (or a pest) is a species that interferes negatively with human activities or aspirations, and it might be native or introduced. A **colonizer** establishes during the initial stages of ecological succession, being replaced in subsequent successional stages – it is the only category defined by biological traits – and it might be native or introduced. **Invasive** species, accordind to the same author, are those coming from other regions – this is a geographic definition.

At a geological time scale, the distribution of species on the surface of the planet has been affected by **climatic or geomorphologic changes of global scale** (Vermeij 1991). Accompanying those changes, biological invasions have been an important factor in the evolutionary process. Such invasions have included small expansions or shifts of species distribution ranges up to invasions of continental magnitude (Huenneke 1997, Williamson 1996, Fryer 1991).

After the end of the **last quaternary glaciation (**between 10000 and 15000 years ago**)**, the development of **human activities** (agriculture, trade, intercontinental travel) led to considerable global environmental changes and stimulated the translocation of living organisms to new regions, purposefully or accidentally, resulting in an increase in the incidence of biological invasions and of species extinctions (Shigesada & Kawasaki 1997). Since the beginnings of agriculture, humans have been an important biogeographic factor, affecting and accelerating the expansion of commensal species (Le Floc'h 1991). Some of those species were intentionally introduced for food, medicine or aesthetic reasons, while others were accidental introductions, imported as crop contaminants or by other means (Rejmánek *et al*. 1991). That is, the first introductions associated with human activities occurred during prehistoric times, including the Paleolithic (Australia), but also along Classic Antiquity (Mediterranean); undoubtedly, it was an event generalized to several regions, including the Atlantic as well as the Pacific (see Capdevila *et al*. 2006).

Beginning in the **16th century,** European civilization promoted a wide exchange of living organisms in tropical areas, particularly on islands; later, the development of botanical gardens, especially in UK, led to the establishment of a network for more systematic species exchange among different regions (Cronk & Fuller 1995). In fact, the 17th century was an important mark in the process of alien species acclimatization (Capdevila *et al*. 2006).

In the **19th century**, the trade pattern led to a considerable flow of species from Europe and to the creation of a large number of societies devoted to the acclimatization of alien species**.** In the 20th century, transportation means increased in terms of speed and capacity to carry living organisms; the duration of trips became shorter and the use of ballast water became common. Presently, however, trade flows are wider and much faster, and species travel in all directions. **The majority of the biological invasions are now originated by human activities** (Williamson 1996). Even in some cases when an invasion is considered to be natural, it is concluded afterwards that the range expansion occurred, most likely, due to changes in the habitat associated to human action (McCulloch & Stewart 1998). The immigration of new species due to human action is much faster and more extensive than that caused by animals, wind and marine currents (Mooney 2005, Raunkjaer 1936).

Although quarantine systems exist, the expansion of human populations, development of railways, proliferation of roads and vehicles, soil movements, and trade of alien species have allowed many opportunities for the introduction and dispersal of living organisms (Ernst 1998, Hodkinson & Thompson 1997, Rejmánek *et al*. 1991). Moreover, the areas where natural ecosystems are directly affected by human activities are steadily growing, increasing the probability of successful invasions (Shigesada & Kawasaki 1997). Consequently, the rate of occurrence of biological invasions has increased to unprecedented levels (Huenneke 1997).

The problems associated with invasion biology are not only of academic interest, but are of considerable importance to **human society** (Mooney 2005). The majority of introduced species do not become successful invaders; however, the cumulative effect of the species that do become successful invaders is considerable. In fact, a considerable number of alien species have become pests or weeds, causing losses in productivity for agriculture, cattle breeding and forestry, and leading to more difficulties in the management of nature reserves (Williamson 1996).

Furthermore, in some cases, it is difficult to solve the problems created by a species introduction because the invader might be considered noxious by one part of society and as beneficial by another sector. Management strategies will have to be searched for that will satisfy the different sectors, which will not be always easy.

The **invasion process** varies according to multiple factors, namely: the traits of the invasive species, the traits of the invaded ecosystem, and the interactions with native species (Lockwood *et al.* 2006). The majority of the invasions occur in habits affected by human activities, particularly those under considerable disturbance, but this might only be a consequence of the fact that species are more easily transported to those sites (Williamson 1996). Undoubtedly, invasions occur also in natural ecosystems (under natural disturbance), and those are our main concern in this book.

In biological invasions, it can be helpful to address some general questions (Shigesada & Kawasaki 1997): what are the conditions associated with an invasion; how is the invasion spreading spatially and at what rate; what are the traits of an ecosystem after successive introductions; which species will become more invasive; what type of habitat will be more susceptible to a particular invasion; what is the impact of the invasive species on native biota. However, predictions about the result of a new invasion are still unreliable (Williamson 1999).

While global change associated with human activities has lead to the decline of many species, it also caused the proliferation of many others, resulting in considerable impacts on native populations and ecosystems. However, research in conservation biology tended to proceed, to some degree, isolated from that of invasion biology. When the conservation of ecosystems, and not only the conservation of native species or populations, gained importance, invasive species became of inherent interest to conservation biology. This has led to a connection between the "science of rarity" and the science of "aggressivity" (Parker & Reichard 1998).

The complexity of the study and management of biological invasions will be further complicated by the other global changes in the biosphere (Huenneke 1997), namely increasing levels of atmospheric CO_2, increase in UV radiation, climate change, pollution by sulfates, increased deposition of nitrates, habitat fragmentation, changes in disturbance regimes (fire, hydrology), and changes in biotic interactions.

Concepts and definitions

Probably, the most important question in biological invasions is to determine what allows a new species to invade a particular ecosystem (Parker & Reichard 1998). However, more basic questions are still unclear. For instance, in relation to invasive plants, Heywood (1989) pointed out the fact that in many floras the reasoning used to classify a species as native or introduced is not explicit, giving the impression that the decision was copied from other authors or based on intuition. In fact, it is often difficult to distinguish between native and introduced, casual and naturalized. Furthermore, a large number of terms are used: indigenous, native, autochthonous, exotic, imported, introduced, non-indigenous, alien, invasive, archaeophyte, neophyte, etc. (see Capdevila *et al.* 2006 for discussion).

The scale at which invasion is considered has also varied widely. A species might be native of the region or country in question, but not to a particular community (Heywood 1989). The invasion of new communities within the native distribution range should be recognized, since its impact might also be significant (Rose 1997a).

Some of this variation in the definition of an invasive species might be an outcome of the fact that a biological invasion is a **dynamic process** and not a localized event, during which the invasive population will go through different stages (Deacon 1991). Thus, the invasion process has been divided into different stages (Figure 1).

Many species show a relatively long initial stage after introduction, during which their numbers are kept somewhat constant – the latency or lag phase (Le Floc'h 1991). Certain environments might function as refuges, from which the species can propagate, when conditions become adequate. Once naturalized a species can enter a phase of expansion (Ribera & Boudouresque 1995), either an ecological expansion – occupation of different biotopes, or a geographic expansion – increase in geographic distribution area. One general rule is that about 10% of the introduced species will become naturalized, and 10% of those will become noxious (Smith *et al*. 1999, Parker & Reichard 1998, Williamson 1996, Leach 1995). This is only a rough guideline, and it is common for transition rates to range from 5-20% (Williamson 1996).

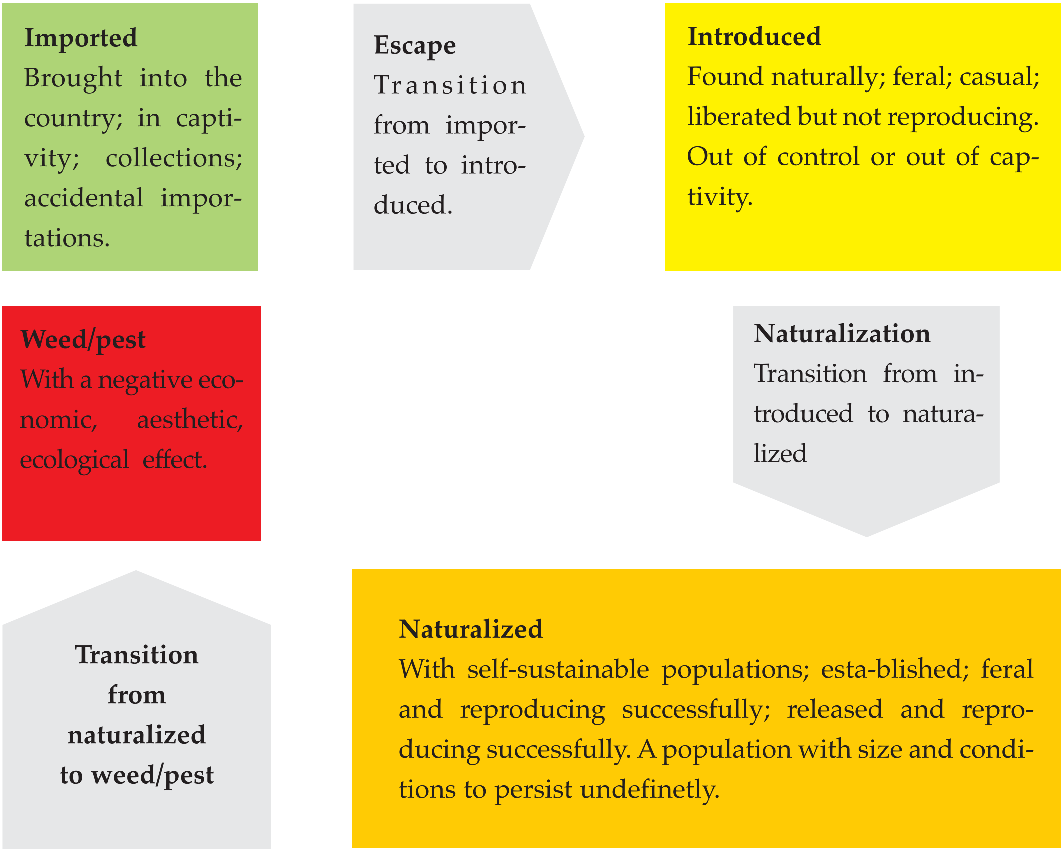

Figure 1. Stages and transitions in the invasion process (based on Williamson 1996).

Presently, the International Union for Conservation of Nature (IUCN) definitions consider that the term invasive should only be applied to those species which have a negative impact on biodiversity, and this is the basis for the definitions used by Convention on Biological Diversity (CBD). In this book, considering the main focus on management, we will follow the basic definition suggested by CBD and IUCN (Tables 1 and 2).

Invasive species

Although the **traits of invasive species** have been widely studied, no research has demonstrated the ability to predict, with confidence, the result of a particular invasion. In fact, there are doubts that the study of the species traits linked to successful or unsuccessful invaders might be useful in predicting the outcome of a particular invasion (Williamson 1999, Simberloff 1989, Noble 1989).

Table 1. Comparison among some definitions related to invasive alien species, according to the IUCN and CBD.

IUCN **Native species**: a species, subspecies or inferior taxon which occurs within its natural range of dispersal potential.
IUCN **Alien species**: a species, subspecies or inferior taxon which occurs outside of its natural range of dispersal potential, including any portion, gamete, or propagule, which might survive and reproduce.
CBD **Alien species**: a species, subspecies or inferior taxon introduced outside of its natural distribution range, including any portion, gamete, seed or propagule, which might survive and subsequently reproduce.
IUCN **Alien invasive species**: alien species which established in a natural or semi-natural ecosystem and is an agent for change and a threat to native biodiversity.
CBD **Alien invasive species**: alien species which by introduction or spreading threatens biodiversity.

Furthermore, a species can become an invader without changing its traits, only due to changes in the habitat. Thus, invasive traits might work as indicators of risk and not as definitive predictors.

In the case of **insects**, population growth rate, food habits, the range of tolerance for environmental factors, size and dispersal ability might be important, but not conclusive indicators of invasiveness (Simberloff 1989).

Regarding **vertebrates**, it was suggested that the comparison of closely related species with different success as invaders might bring new ideas for analysis (Ehrlich 1989). However closely related species may have completely different success as invaders: one might be an invader while the other a rare species (Wade 1997, Williamson 1996). Apparently, invasive vertebrate species, in general, tend to originate from extensive, non-isolated, continental areas (Brown 1989).

Table 2. Comparison among some definitions related to the introduction of species, according to the IUCN and CBD.

IUCN **Introduction**: movement, by an human agent, of a species, subspecies or lower taxon, including any portion, gamete or propagule which might survive and reproduce, outside of its natural area.
CBD **Introduction**: movement, by human action, indirect or direct, of an alien species outside of its natural environment.
IUCN **Intentional introduction**: a deliberate introduction by humans.
CBD **Intentional introduction**: movement and/or deliberate liberation by humans of an alien species outside its natural environment.
IUCN **Non intentional introduction**: an introduction resulting form a species using human or human distribution systems as dispersal vectors, outside its natural distribution area.
CBD **Non intentional introduction**: Other types of non intentional introduction.

There were also attempts to summarize the traits of invasive **plants** (Baruch *et al*. 2000, Reichard 1997, Rejmánek 1995, Ramakrishnan 1991, Noble 1989). Some of these traits included trees more than 3 m high, including also perennial species; effective mechanisms for short and long distance dispersal (birds, mammals, wind, water); early maturity, high flower, fruit and seed set, and high seed longevity; vegetative propagation; high rate of carbon assimilation; shade tolerance; adaptations to fire; acclimatization potential or plasticity; species with secondary substances that are repellent to herbivores.

Regarding **aquatic plants**, several traits have been suggested (Ashton & Mitchell 1989), namely a rapid vegetative growth, the ability to regenerate from fragments, total or partial independence of sexual reproduction, dispersal by human activities, a morphology maximizing the occupation of the euphotic zone, tolerance to variable substrate and water levels, morphological and reproductive plasticity, and production of a large number of small seeds.

It has also been suggested that there might be a relationship between invasion success and abundance or a wide distribution in the native range or with the climate zones or continents invaded (Le Floc'h 1991). In several cases it was found that **previous success as invader** in other regions was an important attribute of a successful invader (Maillet & Lopez-Garcia 2000, Goeden 1983) This might suggest that the biology of the invader could be more important than the particular traits of the invaded community. However, each trait has to be evaluated considering the particular habitat where the invasion might take place (Noble 1989). It is the invaded ecosystem, as much as the traits of the invader that will determine success or failure. It is also considered that invasive species in natural habitats might not depend on the same factors that are important in disturbed areas (Parker & Reichard 1998). Regarding genetics, invasive species show a wide range of traits (Williamson 1996).

In invasion biology, a close evaluation of the **habitat** and study of the natural history of the invader might lead to more valuable conclusions than predictive models based on general species traits alone (Simberloff 1989, Noble 1989). It is improbable that we might predict the outcome of a particular invasion (Milberg *et al*. 1999, Brown 1989, Ehrlich 1989,). In conclusion, the questions regarding the existence of a particular set of traits that will be present in a successful invader might not be pertinent, since the factors that make bacteria successful invaders, will not apply to fish, and the reasons behind the success of different fish, might be completely different (Fryer 1991). However, although the study of traits that will favor invasion has not given conclusive results, the application of statistical modeling to data bases including successful and unsuccessful invaders has generated some useful predictive protocols (Parker & Reichard 1998), included in what is now called **risk analysis**.

The invaded habitat

Barriers that oppose the invasion by a new species include abiotic and biotic factors: competition with established species, natural enemies in the new habitat, absence of co-adapted organisms (pollinators, dispersal agents), climate extremes and seasonality; disturbance regimes, and substrate chemical composition (Simberloff & Von Holle 1999, Williamson 1996, Rejmánek 1989, Heywood 1989).

One of the questions in invasion biology is the possibility that some ecosystems might be more vulnerable than others to invasion (Rejmánek *et al*. 1991). **Invasibility** is defined as the susceptibility of a community to the establishment of species from the outside, either indigenous or native (Lavorel *et al*. 1999). The two factors more generally mentioned as affecting the susceptibility of a community are species richness and disturbance regime (Williamson 1996, Simberloff 1989). The idea that **islands** and disturbed habitats are more susceptible to invasion is based on the assumption that habitats with low numbers of species will be more susceptible to biological invasions (Simberloff & Von Holle 1999, Wiser *et al*. 1998, Moore 1979, Brown 1989, Vitousek & Walker 1989,). However, empirical studies have shown contradictory results (Lavorel *et al*. 1999). Furthermore, the difference for islands might be less a question of vulnerability but a combination of a low number of native species, a larger proportion of changed habitat and a considerable enthusiasm for deliberate species introductions in the past (Williamson 1996). Moreover, continental species might have more chances to invade islands than the opposite (Simberloff 1989).

On the other hand, communities might be more easily invaded by a species of a different type (functional group) not previously represented (Lavorel *et al.* 1999, Wiser *et al*. 1998, Deacon 1991). In islands, there has been minimal resistance to the invasion by certain groups, which are able to explore new ecological niches (Table 3).

Another important factor in biological invasions is the **disturbance regime**, endogenous or exogenous (Baruch *et al*. 2000, Di Castri 1991). Disturbance is any event, relatively discrete in time, which causes a change in ecosystem, community or population structure and alters the resources, the availability of substrate or the physical environment (Hobbs 1989). Meanwhile, there is not complete agreement about the need for disturbance as a prerequisite for invasion. Several authors considered that openings in vegetation cover and associated disturbance (natural or anthropic) are the most important factors in the promotion of invasions of natural and semi-natural communities (Dietz *et al.* 1999, Paynter *et al.* 1998, Parker & Reichard 1998, Duggin & Gentle 1998, Gentle & Duggin 1997, Rose 1997, Williamson 1996, Byrne 1992, Ramakrishnan 1991, Rejmánek 1989).

However, ecosystems that have experienced long periods of continuous or intermittent disturbance are more resistant to invasion and some of their species are considered as highly invasive (e.g. the Mediterranean region). Furthermore, even habitats with low levels of human disturbance, namely nature reserves, show some susceptibility to biological invasions (Usher 1991). The only group of nature reserves that seems to show no introduced species correspond to the protected maritime areas in the Antarctic (Usher 1991).

Table 3. Factors explaining a possible susceptibility of oceanic islands to biological invasions (based on Loope & Mueller-Dombois 1989).

Evolution of island organisms in isolation

- Reduced number of species, low competition.
- Absence of large herbivores.
- Absence of ants, rodents, carnivore mammals, reptiles, amphibians, diseases.
- Disharmonic flora and fauna: absence or rarefaction of plant families and absence of insect orders.
- Dependencies for pre-germination treatment and pollination.
- Low fire frequency and intensity.
- Absence of generalist natural enemies.

Human changes of island environments

- Early colonization by man, leading to a long history of introductions.
- Small area in relation to the potential to support a considerable human population.
- Relatively large area dedicated to agriculture, hunting and other activities.
- Contact with western countries - they are the cross-roads of intercontinental traffic.
- Due to small size, ecosystem use and change extend to entire island; dispersal is fast with different communities spatially very close.

Other factors that might be related to susceptibility to invasion include habitat fragmentation (Suarez *et al*. 1998, Rose 1997a, Byrne 1992), the successional stage of a community, with early stages and ecotones being more susceptible (Stromberg *et al.* 1997, Byrne 1992, Ramakrishnan 1991, Rejmánek 1989). Meanwhile, many authors still question whether some communities are really more susceptible than others, due to several reasons, including differences in propagule pressure (Parker & Reichard 1998, Wiser *et al*. 1998, Williamson 1996, Brown 1989).

In general, **many different types of communities** have been invaded to different degrees: warm temperate (+), subtropical, cold temperate, tropical (-) (Le Floc'h 1991); mesic habitats (+), arid zones (savanna, dry woodland) (-) (Stromberg *et al*. 1997, Rejmánek 1989); humid tropical forest (more invaded on islands) (Whitmore 1991, Connant *et al*. 1997); complex tropical fish communities (Fryer 1991); swamps, wetlands and estuaries (Philbrick *et al.* 1998, Turner *et al*. 1998); marine environment - a vast array of organisms both animals and plants, mainly associated with ballast water (Ruiz *et al.* 1997, Ribera & Boudouresque 1995).

Abiotic environmental conditions have also been reported to affect invasion in different communities: soil/water nutrients, light availability (Wiser *et al*. 1998, Gentle & Duggin 1998, Madsen 1998); rain fall (Lonsdale 1993); changes in topography or in landscape structure (Thomas 1998, Hutchinson & Vankat 1998).

It has also been suggested that introduced species might interact in a positive way, facilitating their establishment, and a synergy might exist leading to a larger effect than the sum of the effects of isolated species. This hypothesis was named "*invasional meltdown*" (Simberloff & Von Holle 1999). As an example, the action of introduced animals might favor the dispersal of many invasive plants (Schiffman 1997).

Predictive models

An important factor in the success of a species as an invader is **propagule pressure**, the number and frequency of introductions over time. The more propagated a species is by human action, the more likely it will be recorded as introduced or established (Lockwood *et al.* 2005). If propagules are introduced repeatedly or regularly, this might lead to naturalization if favorable environmental conditions are present (Le Floc'h 1991). The larger the number of propagules the higher will be the probability of successful establishment: more individuals – higher probability of reproduction – higher probability of finding a favorable habitat, and survive adverse climate and the action of parasites and pathogen (Williamson 1996). Moreover, **chance and timing** affect biological invasions. The arrival to a new ecosystem is influenced by several random events and circumstances (Crawley 1989), namely a founder effect, age, physiological condition, probability of dying before reproduction, abundance of natural enemies or vectors, existence of a refuge, phenology of the resources, and successional stage. We know the attributes that increase the probability of success but are not in a position to make confident predictions about individual cases (Maillet & Lopez-Garcia 2000). Thus, there are few bases to predict the outcome of a particular introduction in a particular habitat, so that until the end of the **20th century** invasion biology was considered as the study of **general tendencies and particular cases**. The behavior of individual introductions is somewhat unpredictable, since there are important differences even between islands of the same archipelago or between species of the same genus (Brown 1989). However, **risk analysis** is already included in the routine obligatory procedures that determine both the decisions regarding intentional introductions and the choice of the most effective management approaches, at least in some countries (Capdevila *et al.* 2006). This type of analysis might be used to estimate the invasive potential of a particular species, to evaluate the risk associated with different introduction pathways, to evaluate the vulnerability of the receptor systems, or to evaluate species that should be included in white lists. In this book, we have developed and applied a risk analysis to the invasive species in Macaronesia, since several items or subcriteria were included that allow assessment of the present and future invasive ability of the analysed species.

Impact

Thorough studies of the impact of biological invasions have been limited due to the fact that, in general, research only starts after the expansion of the invader has already initiated and only for those species already known to have an effect (Parker *et al*. 1999). Furthermore, aesthetical or psychological factors might influence the general public's evaluation of the impact caused by an invader, overemphasizing the impact if it is an offensive or noxious species but minimizing the evaluated impact in the case of an attractive species or if it gives the impression of fitting in the invaded community (Parker *et al*. 1999).

Invasive species compete with native species for limited resources and alter ecosystem function and disturbance regimes (Parker & Reichard 1998). The invasions that most dramatically affect the invaded systems generally involve organisms with a new life form, not previously represented in the community, or invasive species that alter disturbance regimes (Parker *et al.* 1999, Walker & Smith 1997, Williamson 1996, Macdonald *et al*. 1989). The impact of invasive species may be recorded at five different levels (Parker *et al*. 1999): genetic, individual, population, community and ecosystem levels. More objectively, according to the Red Book of IUCN (www.redlist.org), IAS are threatening 5.4% of the endangered species (1284 of 23675).

The invasion of islands by mammals has been considerably damaging, especially where there were introductions of large **herbivores** and **predators** where they were not previously present (Mack *et al.* 2000, Usher 1991). In fact, regarding islands, 27% of the native mammals were extinct after human settlement and the introduction of commensal species (Alcover *et al.* 1998). Introduced predators are the main cause of extinction, and appear to be responsible for 42% of bird extinctions on islands and for the majority of mollusk extinctions (Brown 1989). In the islands of Santa Helena and Ascension and also in several islands from the Indian and Pacific oceans, herbivore mammals were introduced and left to roam freely on the islands, which had a considerable impact on the native flora (Ramakrishnan 1991, Melville 1979, Rauh 1979). Species like largemouth bass (*Micropterus salmoides*), mosquito fish (*Gambusia* spp.), goats (*Capra* spp.), rats (*Rattus* spp.), fox (*Vulpes vulpes*) and the cat (*Felis silvestris catus*), among many others had profound effects on the fauna and flora of the invaded ecosystems. Undoubtedly, the impacts of alien vertebrates in island ecosystems with poor native faunas were larger than in large and less isolated areas (Brown 1989, Macdonald *et al*. 1989). Also, regarding invertebrates, reductions in native species richness have been recorded after the introduction of alien species, namely of ants (Cole *et al*. 1992, Holway, 1998b).

Regarding **invasive plants**, several impacts are known (Table 4). Furthermore, invasive plants may form hybrids with closely related native species, and in some cases the introduced and hybrid taxa might grow and disperse more rapidly (Paiva 1999, Vilà & D'Antonio 1998, Macdonald *et al*. 1989). However, hybridization problems may occur not only in plants but also in animals, namely fish, birds, mammals and insects (Usher 1991, Macdonald *et al*. 1989). Undoubtedly, invasive plants are potent agents of environmental change at the local, regional and global scale (Turner *et al.* 1998). Some examples include *Salvinia molesta* which invaded water streams that previously had no floating plants; *Tamarix* spp. (Tamaricaceae) with its roots that are able to absorb water from deeper soil levels than native plants (DiTomaso 1998); firetree (*Morella faya*) in Hawaii which invaded volcanic soils where no nitrogen fixing trees existed before (Vitousek & Walker 1989, Vitousek *et al*. 1987).

Impacts on aquatic ecosystems have also been recognized (Table 5), due to species competition, predation, and habitat alteration (Leach 1995).

In **nature reserves** biological invasions have several implications, namely a considerable portion of management funds go to control actions, invaders affect local dependent human populations, and they cause a reduction in local biodiversity (Usher 1991).

In general, there is no system for the quantification and comparison of the total effect of invasive species (Parker *et al*. 1999). It was suggested that such a system should include the affected surface area together with the abundance and the effect per individual of the invasive species.

Table 4. Impact of invasive plants on the invaded ecosystems (according to Pickart *et al*. 1998, Parker & Reichard 1998, Turner *et al*. 1998, Blank & Young 1997, Duncan 1997, Wade *et al*. 1997, Walker & Smith 1997, Silva & Tavares 1995, Mitchell & Gopal 1991, Usher 1991, Williams & Timmins 1990, Macdonald *et al*. 1989, Vitousek & Walker 1989).

- Monospecific stands, excluding native flora and leading to a reduction on diversity.
- Affect the basic mechanisms of ecosystem function (productivity, water regime, water runoff and erosion, sedimentation and geomorphology, evapotranspiration, rain interception, infiltration).
- Alteration of the disturbance regime (fire, landslides).
- Affect nutrient cycling and soil chemistry (nitrogen fixation, nutrient consumption, addition of salts).
- Make new food sources available (for exotic animals).
- Alter the use of the invaded habitat by local fauna (vertebrates and invertebrates).
- Cause the decline of mycorrhyzal fungi.
- Change the natural or traditional landscape, to which humans were familiar.
- Block trails and cause allergies.

Table 5. Impact of biological invasions in aquatic ecosystems (based on Findlay *et al*. 1998, Madsen 1998, Strayer *et al*. 1998, Kolar *et al*. 1997, Mitchell & Gopal 1991, Ramakrishnan 1991).

Dense stands of invasive plants

- Reduction in dissolved oxygen.
- Increase in water temperature.
- Increase the internal nutrient load.
- Reduction in the diversity of macro-invertebrates and a reduction in fish growth.
- Alteration of water flow.
- Serious social implications due to effect on circulation, fishery, irrigation, hygiene, drinking water supplies, and on hydroelectric power stations.

Invasions by bivalves and zooplankton

- Changes in the relative abundance of bacterio- phyto- and zoo-plankton.
- Changes in water quality.
- Changes in benthonic communities.
- Changes in the trophic chains.

Although the first two values might be obtained with more or less difficulties, the same might not apply to the associated effect. Furthermore, while a **researcher** might be interested in measuring impact in order to test hypotheses regarding community or ecosystem function, or to understand the factors underlying invasion, the **manager** of a nature reserve will need to measure the impact in order to identify target species and priority intervention sites for control actions (Parker *et al*. 1999).

Williamson (1998) suggested several means to quantify the impact of invasive plants: records of invasive species in nature reserves, estimates of the cost of control operations, the average tendency to become invasive as given by a panel of experts, and the number of records at different sites.

Undoubtedly, biological invasions also cause **economical impact**, in some cases, of considerable scale. These include loss in the potential output of human activities (agriculture, cattle breeding, fisheries), damage of stored products and damage to infrastructure. Moreover, the costs associated with control actions should also be taken into account. This includes all the necessary measures related to quarantine, early detection, control and eradication. Globally, IAS are responsible for economic losses on the order of the hundreds of million dollars in several countries (see Capdevila *et al*. 2006). Moreover, in Europe, for instance, the investment through the EU-Administered LIFE program has ascended to hundreds of millions of Euros. Furthermore, some authors consider that many of the epidemics that have affected and are presently affecting mankind also resulted from biological invasions.

Despite all this knowledge, some authors claim that few invasions have caused extinctions, and also that introductions tend to add species and not to cause extinctions (Wade 1997, Pimm 1989). This opinion might be due to fact that the real effect of an invasive species in the invaded community is often difficult to evaluate, in particular because there is no information available about the initial structure of the community and its ecological processes (Parker *et al*. 1999).

Prevention

During the history of mankind several reasons and motivations have justified the **intentional** introduction of alien species (Capdevila *et al*. 2006). These include economic activities (agriculture, horticulture, ornamental species, forestry – timber production, soil improvement, erosion control - fishery, hunting, biological control of pests, etc.), scientific or educational activities (zoos, botanical gardens, etc.) and aesthetical or psychological factors (landscaping, pets, gardening, etc.). In reality, the quality of life presently available in many countries is largely dependent on the plant and animal species that were introduced. This human dimension is an essential element when determining the legal, financial and penal mechanisms that should be implemented in order to discourage the economic and importation activities that involve high risks (Jenkins 2001). In this regard, cities are focal points of the global economy and are thus the point of entry of many alien species, while the dispersal of many of those species proceeds through the transportation systems and along corridors (Capdevila *et al*. 2006).

On the other hand, **accidental introductions** occur by means of different pathways (Capdevila *et al*. 2006). These pathways clearly include shipments of agricultural products, wood, flowers, plants and seeds; encrusting species on boat structures; discharge of ballast waters; destruction of geographical barriers by engineering projects; importation of living organisms as vectors or dispersal agents; accidental "travelers" in long distance transportation means (aircrafts, ships); anthropochory in vehicles, equipment, clothes, shoes, etc.; shipment of merchandise (containers); packaging materials (wood, boxes, pallets, etc.).

Some authors (Capdevila *et al.* 2006) also consider **negligent introductions**, when there is no aim to establish a feral or naturalized population but the necessary measures to avoid species escape were not taken. Examples include escapes from farms, zoos, aquaculture, aquariums, etc. as well as careless disposal of ornamental plants.

In the **regulations** regarding the entry of alien species, the importation of organisms that will be kept in strict captivity (e.g. for zoos or laboratory research) should be clearly separated from species that are not kept in strict captivity or quarantine. In the first case, the risks are mainly associated with the possibility of escape of the organisms and their survival in the external environment. In the second case, the risks are linked to the possible impacts of those organisms in the ecosystems (Levin 1989). Additionally, we should also consider the importance of accidental and illegal introductions since many of the more destructive biological invasions took place through this pathway (rodents, termites, many agricultural weeds, agricultural pests, illegal release of mustellids by animal protection organizations).

The issuance of **permits** for the importation of organisms has been largely focused on preventing the entry of species recognized as threats to agriculture, horticulture, forestry, cattle breeding, and public health, while avoiding impacts in the native flora and fauna has been of lesser concern.

In the case of alien plants, **black lists** of species that are not allowed to be imported and **white lists** of plants and organs that may be imported have been used. For those species that are not listed, specific permits should have to be issued. Approaches using black lists and white lists differ in philophophy: using black lists assumes that most introductions, except those listed, will probably be safe. The use of a white list implies that listed species will never be a problem, but unlisted species are a potential risk. Meanwhile, this more restrictive view is difficult to accept by several sectors, including the pet industry, collectors, hunters, farmers, plant nurseries, aquariophyles, and aquacultures. On the other hand, a clear compromise might exist allowing an expansion of the black lists combined with the use of white lists, the remaining cases being subject to a special permit (Table 6).

According to Reichard (1997) the introduction of a species should be prohibited until it has been demonstrated to have a low probability of becoming problematic. The evaluation costs would be supported by the importer, and as a compensation the importer receives exclusive importation rights for a specific time period (Reichard 1997). Once evaluated, the species would be included on the white or on the black list, which would serve as guidance for future requests. In Australia, some problems with the public and the nurseries became apparent after a proposal to prohibit the use of certain species in gardens was issued (Rose, 1997b). Moreover, several authors have suggested that the possible use of native species in socio-economic development should be evaluated before considering the introduction of alien species (Usher 1991). Legislation might enforce the control of a particular species and promote its regulation (Ashton & Mitchell 1989). However, the prohibition of the use of one species will always be contentious and thus will have to be based on solid grounds. In Portugal, the possession and sale of water hyacinth (*Eichornia crassipes*) were prohibited through a decree (Decreto-Lei 165/74 de 22 de Abril), but it has been difficult to implement this measure (Paiva 1999).

The **CBD** requires that the contracting states, to the degree that it is possible and appropriate, prevent the introduction and, control or eradicate those alien species which threaten ecosystems, habitats or species. Many other guidelines exist, issued by different entities, but they function only as recommendations.

Table 6. Some principles for the regulation of importation/introduction of living organisms (based on Ribera & Boudouresque 1995, Levin 1989).

- Deliberate introductions: national permit (national and international scientific committee).
- Demonstration by the interested entity of the economic importance and of the lack of alternatives (native species).
- Evaluation of the risks associated to the introduction.
- Evaluation of the probable destiny and of the probable effects of the biological material.
- Review and consideration of other information including: traits of the introduced species, control methods, aims of the introduction.
- Do not perform introductions when there are no control strategies available.
- Stimulate the application of good practice codes at importation level.
- Passing responsibility to the importer.
- Delimitation of biogeographic regions: control, decontamination and quarantine of the biological material transported between regions.
- Monitoring after the introduction.
- A plan for biological and physical containment.
- A plan to mitigate possible adverse secondary effects.

The International Plant Protection Convention (CIPF 1971), requires that the contracting partners issue certificates for plant exportation and allows governments to stop the introduction of certain products due to phytosanitary reasons. Legislation has also been produced by the European Union aiming to increase phytosanitary precautions during the circulation and importation of plant material (Graça *et al*. 1993). On the other hand, the European Community Habitats Directive (Council Directive 92/43/EEC), which seeks to maintain and restore natural habitats and wildlife, is somewhat unspecific considering the regulation and possible prohibition of deliberate species introductions, and accidental introductions are not mentioned at all. In general, until very recently, legislation had not predicted the eventual need of taking control measures, in the case of the escape of introduced living organisms.

In some countries the **legislation** relating to species importation is more comprehensive, namely in Germany, Switzerland, New Zealand and Australia. However, even in Australia, where legislation is considerably strict, 20 to 30 species continue to become naturalized each year (Ribera & Boudouresque 1995). In Central Europe, the number of introduced plants has been steadily growing through the 1980's and 1990's, increasing about 90% in 13 years (Pysek & Mandák 1997). Up to the end of the 20^{th} century, laws have been considered ineffective in containing the wave of introductions because noxious weed laws have focused on a narrow range of pests of agriculture, and have generally failed to prohibit introductions of natural area invaders (Daehler *et al.* 2004). When natural area invaders have been prohibited through legislation, it was usually only after they reached a point where control would probably be too expensive or ineffective (Reichard 1997).

In **Portugal**, a decree from 1999 (Decreto-Lei n.º 565/99 de 21 de Dezembro) aimed to limit the introduction of alien species of fauna and flora in nature, with the exception of those devoted to agriculture. One annex to the decree lists the alien species considered as posing ecological risk, establishing an option for the system of black lists. Moreover, the decree generically prohibits the intentional introduction of alien species in nature, aiming to promote the use of native species if adequate for the same purposes. Regarding accidental introductions, measures are defined regarding the trade of alien species at confined places, forcing the shops and other entities which harbor those species in captivity to be licensed and to follow minimum security regulations as a way of preventing escapes.

In **Spain** the present systems of prevention show a series of weaknesses (Capdevila *et al.* 2006). Firstly, the environmental considerations constitute only a small component of the decision-making processes regarding the authorization of new introductions. Thus, prevention systems are mainly focused in avoiding the introduction of pests and diseases. Furthermore, information about the introduction pathway of many species continues to be incomplete. Importation restrictions exist only for a limited number of species and the increasing volume and diversity of the merchandise opens new introduction pathways, which are not regulated by the present legislation. Moreover, the present system of control and inspection cannot face the above mentioned increase in merchandise flow because the border offices do not have the adequate human, economic and technological resources, the inspection service is not based on solid statistical sampling models, and the sanctions applied to illegal introductions are inadequate. Meanwhile, from the legal perspective, species introductions are regulated by at least seven different legal documents as well as by the recently approved biodiversity law (Ley 42/2007, del Patrimonio Natural y de la Biodiversidad).

Presently, the guiding principles for a prevention strategy are largely based on the CBD (CBD 2002) and in the European Strategy for Alien Invasive Species (Genovesi & Shine 2004). According to the later, the focus should be directed to **precaution**. The lack of scientific certainty about the diverse consequences of an invasion should not be used as a reason to delay or abort the adoption of adequate measures for eradication, containment or control.

Education is an important strategy of prevention, since the participation of the public is crucial to control and prevent biological invasions (Colton & Alpert 1998, Williamson 1996, Cronk & Fuller 1995). There is a considerable lack of knowledge about the risks associated to species introductions, especially plants (Daehler 2008). In studies undertaken by Colton & Alpert (1998) it was shown that, even among citizens with high academic education, only a minority supports the application of considerable effort to control invasive plants. However, in some cases the efforts dedicated to education and inspection have shown to be more effective than quarantines (Schneider *et al*. 1998). To apply more restrictive legislation, it will be necessary to inform the general public about the possible consequences of an undesirable introduction (Reichard 1997). In this regard, nature reserves might play an important role, if integrated into a global education strategy. Several entities at the international level – IUCN, CBD, and Bern Convention – have recognized the value of environmental education as an obligatory tool for prevention.

Priorities and control strategy

Due to difficulties in the implementation of importation regulations and in the prevention of accidental introductions, it is necessary, in many cases to control alien species. In this sense, **monitoring** invasive species along indicative areas (roads, trails, and water corridors) might allow the early detection of new invaders at their initial phase of establishment (Reichard 1997).

Eradication might be the adequate strategy only for those species recently established and with a limited distribution (Sharov & Liebhold 1998). In those cases, decreasing the expansion rate is the first step, and this might be achieved through the elimination of small satellite populations, which occur beyond the invasion front (Sharov & Liebhold 1998). Since the latency phase is generally long (decades) some work might be developed aiming to determine which species are likely to proceed to later stages of the invasion process (Wade 1997). At those later stages, the expansion might be exponential, and the costs for its control will rocket. Without any doubt, alien species will be much more easily **controlled at the initial stages**, although it might be impossible to establish *a priori* which of the species would become more problematic (Woods 1997). Meanwhile, it will always be more reasonable to control a species at its initial stages of invasion if it has been already recognized as a problematic species in other regions (Randall 1997). According to Wade (1997), alien species present in a region should be listed and, among that set, select those which potentially will expand in area or in population size, making them targets for control actions. As an example, in New Zealand, 65 species were listed and considered as priorities, because they caused considerable impacts on native ecosystems (Williams & Timmins 1990). As a general rule, only some of the alien species introduced into an area will cause significant impact in the natural community, thus it will be important to develop and apply an analytical instrument that allows identifying the innocuous species, those that are potentially problematic and those that are already causing impacts. Harris (1992) and Hiebert (1997) have suggested ranking systems for alien species in natural areas, based on the level of impact, on the innate potential to become problematic, and on the probability of successful control.

In general, the management of natural communities where alien species have been introduced and are well established has followed two different philosophical approaches (Luken 1997): i) the traditional way, defined by weed and pest control, involving the application of chemical, physical or biological control methods directed against the problematic species – the success is quantified in terms of the mortality rate of the invasive species; ii) an alternative way, consisting in the development of measures that will oppose the processes which have led to the gradual alteration of the ecosystem – the success is measured through the change in the abundance of both alien and native species involved. In fact, the tendency to focus the attention on the attributes and on the management of individual invaders has been criticized, and an alternative, a more holistic approach has been suggested which focuses on the factors that are increasing ecosystem susceptibility to biological invasions. Moreover, several authors suggest that the control of invasive species should be centered in the ecosystem and not on the species, since invasive species control should be seen as one part of a good **management** system for natural resources (Edwards 1998, Rose 1997b, Woods 1997, Usher 1991, Williams & Timmins 1990).

The management of alien species in natural communities has followed the principle that control of the invaders will allow, eventually, the establishment of a balanced system, dominated by native species; however, this result may have a low probability (Luken 1997). In the recovery of degraded areas the objective may be only to go back to a better condition, in which there will be a restoration of the ecosystem, and not to go back to the original situation with a complete absence of alien species (Randall 1997, Rose 1997b). Moreover, the management measures aimed to eliminate invasive species should consider both native and alien species, with the objective of gradually establishing a dynamic system that will satisfy concrete management goals (Luken 1997). The **success** of a natural area restoration project can be improved through the recruitment of volunteers and with the involvement of the local community, although with guidance from professional staff (Rose 1997b). The most effective control projects were those where a **coordinated management plan** was adopted, and those where the effort was maintained until the established objective was attained. Those projects included the participation of professional staff, volunteers, public, marketing campaigns, educative programs, and research (Williams & Timmins 1990). On the contrary, lack of planning, changes in personnel and funding fluctuation has lead to failure (Table 7).

Finally, it is generally agreed that many alien species have not caused negative impacts. Thus, the decision to control an alien species should be taken case by case and taking into consideration social aspects as well as the values put at stake, avoiding a possible prejudice against alien species *per se* (Edwards 1998, Eser 1998, Kowarik & Schepker 1998).

The future

There are differing opinions about the future. Some authors state that without an effort to protect natural ecosystems, alien species will proliferate and inundate all the ecosystems, with the exception of the more resistant. Others emphasize the possible role of alien species in the changing biosphere (Ribera & Boudouresque 1995, Saxena 1991, Brown 1989). According to Sukopp (1998), the majority of the naturalized species will persist and will become a part of the flora, resulting in new communities.

Table 7. Some principles for the regulation of the effort to control invasive species, including the simultaneous application of preventive, restoration and control measures (based on Rose 1997b, Wade 1997, Ribera & Boudouresque 1995, Williams & Timmins 1990).

- Avoid creating conditions that will increase the gravity of the problem – prevention of new introductions.
- Detect new invasions and take immediate eradication measures - early detection and rapid response.
- Minimize their impact when eradication fails – containment and control.
- Establish management priorities regarding species, sites and circumstances.
- Training and coordination of the different entities involved, particularly those performing inspection at entry points.
- Make a list of problem species for each area/region.
- Map and estimate population numbers and impact.
- Organize the information about alien species from literature and experts.
- Define the priority invasive species according to their impact and the probability of successful control.
- Develop ecological modeling of invasive species supported in geographic information systems.
- Define a management strategy.
- Plan, execute and monitor control using several methods.
- Eliminate all the alien species in small areas of high conservation value.
- Direct efforts to species that cause higher impacts, when there is some probability of success.
- Restore invaded areas using specific methodologies.

Naturalized species might have a higher probability of survival and could constitute the basis for a new diversification. In developing countries, the impacts of invasive species management strategies have a direct connection with social and economic factors, and it was thus suggested that the largest benefit may be derivel from the biomass provided by those species as fuel, food, fodder, fertilizer, in water treatment, and as raw material (Ramakrishnan 1991, Vasudevan & Jain 1991).

The valuation of ecological functions of alien species has been higher in anthropic systems, and their value might increase with the expansion of converted areas or with climate change, if some of the native species happen to be lost (Williams 1997). In relation to plants, a mixture of native and alien species – synthetic vegetation – may be inevitable (Rose 1997b). However, questions remain about the how this departure from the original community might affect the maintenance of the ecological mechanisms that support biodiversity.

Meanwhile, the European Union, through the European Commission, published a Communication regarding the need to stop biodiversity loss: "Halting the loss of biodiversity by 2010, and beyond - Sustaining ecosystem services for human well-being {SEC(2006) 607} {SEC(2006) 621}". Very clearly, one of the priority topics defined by the Communication was the urgency to decrease the impact of IAS on biodiversity. The Communication directs members to "Reduce in a significant way the impact on European Union biodiversity of IAS and alien genotypes".

In the same sense, the Final Declaration of the "European Conference on Invasive Alien Species, Madrid, 15 and 16 of January, 2008" has published the main general conclusions which follow. The threat of IAS is increasing exponentially, leading to extinction of native species, causing imbalances in ecosystems, and impacts in the economy and in public health, thus it is urgent to respond to this threat efficaciously. Prevention is the first response and the most desirable. Regarding mitigation, early warning systems should be implemented as well as mechanisms for the immediate eradication of IAS during the first stages of establishment. A political compromise and the development and implementation of a specific legal document regarding the prevention and control of IAS at European and national levels are considered as a priority. Codes of good practice focused on prevention should be created and national committees dedicated exclusively to IAS should be established. The coordination between research centers and governmental entities is fundamental, citizen participation should be stimulated, and environmental education should be considered as a fundamental tool in IAS control.

We hope that those guidelines will be followed in the near future by all the intervening countries and regions.