Alien plant invasion in Chile: history, drivers, and risks

D i s s e r t a t i o n

zur Erlangung des akademischen Grades

doctor rerum naturalium (Dr. rer. nat.)

vorgelegt der

Naturwissenschaftlichen Fakultät I
Biowissenschaften

der Martin-Luther-Universität Halle-Wittenberg

von

Frau Nicol Fuentes Parada

geb. am: 02.09.1977 in: Parral, Chile

Gutachter /in

1.

2.

3.

Halle (Saale)

Table of contents

Summary

Alien plant species are recognized as one of the leading threats to biodiversity. In addition, this phenomenon impose enormous costs on biodiversity conservation efforts, losses in crop production, forestry, and other human enterprises, as well as threats on human health. Accelerating human trade, tourism, transport, and travel over the past century have dramatically enhanced the spread of the alien plant species, allowing them to overcome natural geographic barriers. However, not all alien plant species are harmful, but those that become invasive can be extremely costly to society. The most effective method (ecologically and economically) of managing alien plant species is to prevent their invasion in the first state (i.e. the initial arrival), and the restriction of naturalization once a species is present or restricting the spread once the species is naturalized. The first step to prevent invasions requires not only good long-term data sets of alien species abundance and distribution, but also knowledge on how they have changed over time, the drivers that are likely to promote them and future risks in terms of the new alien plants introduction.

The studies which comprise this thesis deal with the alien plants introduction in Chile, a territory considered as a continental island, and identified as a hotspot of global biodiversity, due to its remarkably high levels of endemism and biogeographic isolations. In particular, I aims to study the history of alien plants introduction, spread, and the main potential drivers of this process. Furthermore, quantify the importance of human disturbance, socioeconomic activities, and climatic gradients on the current pattern of alien plant species abundance. An additional goal is to contribute to the management of invasive alien plants species developing a priority rating system for their control or eradication.

To study the history of alien plants introductions, I used the increments in the proportion of alien vs. native plant species recorded in the herbarium specimens. The first step of positive and rapid increment of alien plants (1910 to 1940) coincides with a first period of strong growth of Chilean agriculture as indicated by increments in wheat and other cereals production. A second maximum (approximately between 1980 and 2000) occurs in a period when: (*i*) wheat surface goes down but (*ii*) wheat

production increases, and (*iii*) forestry exports increases. These changes are coincident with increased mechanization making possible more wheat production in fewer surfaces.

On the other hand, the current drivers of alien plant species density at province scale in Chile are gross domestic product (GDP), road density, and density of agricultural land. Nevertheless, the density of alien plants is inversely correlated with climate type. I found that the effects of the outlier's provinces with higher GDP (which have more or better mapping schemes) can bias the model, in this case, towards a positive and apparently robust role as predictor of alien plants density. When the outlier provinces were deleted, GDP lost its predictive power, and yet the significance of road density, density of agricultural land, and climate type remained. The drivers changed when the analysis was performed separately for each climate type. In the Desert, temperate-rainy/cold rainy, and cold steppe climate type the most important driver of alien plants density was the density of agricultural land, whereas in semi-desert/Mediterranean climate type was road density. Alien plant density was greater in provinces with Mediterranean and temperate rainy climates, and declined towards both the northern desert areas and southwards to cooler environments.

Chile is expanding its economy, and as a result it can be expecting new introductions of alien plants and increasing of propagule pressure coming mainly from the neighbour's countries. Road margins are probably the most relevant pathway for alien plant exchange between Chile and Argentina, and by this ways with the rest of South America. In terms of the new alien plants introductions risk, Chile represents a higher risk to Argentina than vice versa. Twenty-two alien species exclusive to Chile, and present on road margins connecting both countries, are at the top risk level for Argentina. Additionally, both countries have a similar number of exclusive alien species, but not present along road margins (Chile 162; Argentina 186), which can be a potential harmful to be introduced to the other country.

In summary, my results on alien plant species in Chile clearly indicate that alien plants inhabiting the territory will continue increasing taking into account that the curve of species accumulation is not yet asymptotic. Most of the alien plants species present in Chile concentrate in the Mediterranean and temperate rainy regions, and areas with low densities of alien plants are those with less degree of human disturbance too. This pattern indicates that the level of human activity and climate type directly influence the number of alien plants present in Chile. Road density and agricultural activities resulted to be the major driving forces of alien plant distributions in the country to day. Certainly, these activities offers the chances of bringing in alien plant propagules, and it gives to the alien plants the opportunity to spread and to establish in disturbed landscapes, as well as in irrigated areas under cultivation. As both mentioned activities can not be minimized, a proper monitoring system will be necessary to avoid or reduce new alien plant introductions. The results obtained in this thesis may help to develop a guideline for a sustainable land management, directed at avoiding the expansion of alien invaders by targeting dispersal pathways and limiting anthropogenic disturbances associated with increasing risk of alien plant invasions.

Chapter 1

General introduction

1. On the origin of alien plants

The process of globalization is breaking down the biogeographic barriers that have created and maintained the major floral and faunal regions of the Earth (Vitousek *et al*. 1997a, Mack *et al*. 2000). One of the most severe consequences of globalization is the increase in the number of new species (alien species) being introduced to different ecosystems (Elton 1958, Perrings *et al*. 2005). Alien species have been suggested as one of the major global drivers for species decline in our time, after habitat destruction (Vitousek 1994, Glowka *et al*. 1994, Sala *et al*. 2000). The aggregate effects of human-caused invasions threaten efforts to conserve biodiversity (Mack *et al*. 2000) and sustain natural ecosystems functions (D'Antonio & Vitousek 1992). In this thesis, the term "alien" is used to describe plant species that are not native to a country (i.e. non-indigenous) and whose presence is due to intentional or accidental introduction as a result of human activities (Richardson *et al*. 2000). Here we consider all alien plants that are casual, naturalized, or invasive (*sensu* Richardson *et al*. 2000), but not those that survive only under human cultivation.

Humans move species beyond their native ranges both intentionally and accidentally. Intentionally introduced species comprise those that are cultivated as ornamentals, timbers productions, erosion control, medicinal purpose, and other economic uses (Hulme *et al*. 2008). Accidentally introduced species comprise those that are introduced as contaminants of seeds, adhesion of seeds on domestic animals, soil, and agricultural produce or packing material (Hulme *et al*. 2008). In both cases, the species established self-reproducing populations outside the area of cultivations or point of introduction and spread into natural communities.

Within the last 100 years, the number of established alien plant species increased rapidly in many regions of the world, as a result of increasing trade volume and travel around the globe (e.g. Rejmánek & Randal 1994, Perrings *et al*. 2002, Lambdon *et al*. 2008). The numbers of alien plants in a region are related to several factors that can be distinguished during the invasion process (see below). It has been demonstrated that only few of the many alien species that arrive in a new region actually become to establish there, then only a small percentage of the established species go on to become invasive (Williamson & Fitter 1996). For instance, only 10% of all species introduced into the British flora actually became established, and then only 10% of those were invasive enough to be considered as pests (i.e. *tens rule* Williamson & Fitter 1996). Even though, only a small percentage of the established species go on to become invasive, those that become invasive can be extremely costly to society (see below) (Mack *et al*. 2000, Pimentel *et al*. 2005).

2. The invasion process

Invasions are dynamic processes during which several stages can be distinguished. It starts with the *arrival* of propagules in a given area. It has been shown that propagule pressure (e.g. the frequency and abundance of propagules entering an area) is positively related to the invasion success of a species (Levine 2000, Lockwood *et al*. 2005). After initial successful colonization, the next stage of invasion is characterized by *establishment* of one or several self-reproducing founder population (Sakai *et al*. 2001). It is (commonly) accepted that disturbances (natural or human-made) of an ecosystem favor the establishment of the species (Lonsdale & Lane 1994, Hodkinson & Thompson 1997). Once initial colonization and establishment have occurred, the alien species may *spread*. In this phase, propagules are dispersed and more populations are built up. A successful spread depends on the species ability to disperse.

Invasive species may *spread* by continuing long-distance dispersal (saltation dispersal), from foreign sources (naturally or aided by humans), and by short-distance dispersal (diffusion dispersal) with lateral expansion of the established population (Smith *et al*. 1999, Davis & Thompson 2000). Factors influencing the number of propagules, dispersal mode, and survival rates (births minus deaths) are critical factors regulating the spread of alien plant species (Sakai *et al*. 2001). The next phase may be called *range expansion*, where the species spread not only locally, but across the landscape, colonizing new suitable habitats (Shigesada *et al*. 1995). Successful *spread* and *range expansion* is facilitated if the species has wide ecological amplitude, and is able to survive with a wide range of new environmental conditions (Backer 1965, 1974). Furthermore, the success of an alien plant species depends both, on the species traits (*invasiveness*), and on the susceptibility of an ecosystem to the invasion (*ecosystem invasibility*) (Lonsdale 1999).

3. Impacts caused by alien plants

The impacts of alien plant species are recognized from the local to the global scale. Scientists, land managers, and the general public are becoming more aware of alien plant impacts. The impacts caused by alien plants can be noticeable at different levels: ecological, environmental, social, human health, and economic. The ecological and environmental effects of alien invasive species can be identified at all levels of biological organization including the gene, species, habitat, and ecosystem (Williamson 1996, Vitousek *et al*. 1997a, Mack & D'Antonio 1998, Mack *et al*. 2000). Plant invasions have been shown to have an impact on individuals (including demographic rates), genetics (including hybridizations), population dynamics (age, size or abundance), communities (species richness, diversity), and on ecosystem processes (primary productivity, nutrient availability) (review and references in Parker *et al*. 1999, Mack *et al*. 2000, Pimentel *et al*. 2005). These impacts can be grouped into direct and indirect ones. Direct impacts include competition for space, nutrient, water and light, resulting in outcompeting native species, displacing them with populations of the alien plants and preventing the establishment of native plants (Gaudet & Keddy 1988, D'Antonio & Mahall 1991, Pauchard *et al*. 2003). Ecologically, these effects are due to competition between the alien plants and its neighboring native plants, with the aliens having a superior competitive ability (Blossey & Notzold 1995). Indirect impacts include changing soil water relationship (Blossey *et al*. 2001), alterations of natural disturbance regime (Vitousek *et al*. 1996, 1997a, Chapin *et al*. 1996, Mack & D'Antonio 1998), nutrient cycling (Vitousek & Walker 1989, Yelenik *et al*. 2004), and light conditions (Loh & Daehler 2008), resulting in habitat alterations (Vitousek *et al*. 1997a, Sakai *et al*. 2000). These impacts can alter fundamental ecological properties such as the dominant species in a community, physical features of the ecosystems (Simberloff 1981, Vitousek 1990, Mack *et al*. 2000), and habitats for native animals (Lonsdale & Braithwaite 1988, Trammell & Butler 1995, Pimentel *et al*. 2005).

The full impacts of invasions also include those on the society, human health and economy (Mack *et al*. 2000, Pimentel *et al*. 2005). However, up to day there is no information on the costs of control alien plant species that threats human health, as direct agents of disease or as vectors of parasites (Perrings *et al*. 2005). At the economic level, plant invasions cause two main categories of economic impacts. First, there is the loss in potential economic output: i.e., losses in crop production and reductions in domesticated animal and fisheries survival, fitness, and production. Second, there are the direct costs of combating invasions, including all forms of quarantine, control, and eradication (Pimentel *et al*. 2000). For instance, the costs of control of invasive species and the loss of native species in the United States amount to $ 137 billion annually (Pimentel *et al*. 2000).

Most of the invasive alien plant species were intentionally introduced (Panetta 1993). Consequently, the most effective method (ecologically and economically) of managing them is to prevent their invasion in the first state (i.e. the initial arrival), and the restriction of naturalization once a species is present or restricting the spread once the species is naturalized (Zamora 1989, Westbrooks 1991). The above mentioned impacts and costs make clear that a proper management of invasive alien plants and invaded communities is necessary to prevent their spread to new areas or to reduce the impacts of invaders (Mack *et al*. 2000). The first step to prevent invasions, namely restriction or management of invasive alien plants, requires not only good long-term data sets of alien species abundance and distribution, but also knowledge on how they have changed over time, the drivers that are likely to promote them and future risks in terms of the new alien plants introduction.

4. Alien plants in Chile

4.1 History of alien plant introduction

The history of alien species introduction to South America starts with "*The Columbian Exchange*", which have been described as: "*the most important event in human history since the end of the Ice Age*" (Crosby 1972). The term is used to describe the enormously widespread exchange of plants, animals, food, human populations (including slaves), contagious diseases, and ideas between the Eastern and Western hemispheres that occurred after 1492 (Crosby 1972). Early in the 16th century parts of North and South America was dominated by European nations. This resulted in a tremendous ecological and economical revolution, resulting in profound changes to its landscape, population, and plant and animal life (Crosby 1972).

In the past five centuries, the rate of the interchange of flora and fauna between the New and the Old World has increased considerably (Crosby 1972). In Chile, the Spanish conquest in the 16th century marked the fist introduction of several Old World plant and animal species into the Mediterranean region in Chile (Montenegro *et al*. 1991, Jaksic 1998). The biogeographic characteristics of the territory - which supported the Hispanic Mediterranean farming model - favored the introduction and spread of alien plant and animal species (Torrejón & Cisternas 2002). This resulted in ecological alterations of the territories inhabited by Indians without intense productive systems (Aronson *et al*. 1998, Torrejón & Cisternas 2002). Despite the importance of alien plants in South America in general and in Chile in particular, little is known about the underlying causes of the invasions, historical processes, drivers and risk for native species and ecosystems function. Given that Chile has been strongly isolated from other areas of South America (Arroyo *et al*. 1996, Armesto *et al*. 1998) and is considered a continental island with a wide ecological gradient (Jaksic 1998, Arroyo *et al*. 1999), the territory represent an attractive location to evaluate the introduction and invasion by alien plants as a result of the five centuries of interchange between the Old and New World.

In Chile, in the mid-sixteenth century, fire was used by indigenous people for clearing land for crop cultivation (Arroyo *et al*. 2000). However, pre-European levels of disturbance were minor in relation to the wave set off by such activities as wholesale wood cutting for agriculture, burning of vegetation for crop production, and the introduction of European livestock (Aschmann & Bahre 1977) and rabbits (Jaksic & Fuentes 1991) during the colonial period. The first deliberate introduction of alien plants into Chile was in the 16th century by the Spanish colonizers (Montenegro *et al*. 1991, Jaksic 1998, Arroyo *et al*. 2000). Scientific descriptions and collections of the

Chilean flora date from the 18th century, and were carried out by naturalists interested in the native flora, not in alien plants (Figueroa *et al*. 2004). Later, during the 1850s, the introduction of alien plants was promoted by different governmental agencies (Castro *et al*. 2005). Alien plants were imported through exchange programs with European institutions with the purpose of using them in teaching, botanical medicine, and in the search for new crops (Philippi 1882). Around 2,000 alien plant species were cultivated for their study and propagation in the Botanical Garden of Santiago (Mostny-Glaser & Niemeyer-Fernandez 1983), although in time it came to hold more than 3,000 species (Marticorena & Rodriguez 1995).

Although alien plants were reported in Chile since colonial times in the 16th century, little is known about the history of introductions and fluctuations of abundance of alien plants (see chapter 2, this thesis). The exact dates of introduction as well as the number of introduction events are difficult to establish, because many alien plants have been introduced unintentionally into the country (Arroyo *et al*. 1995). In this context, data stored in herbarium records is at present the main and most reliable source of historical information available of alien plants in Chile. Although herbarium records are heterogeneous in terms of location, habitat description, and have limitations mostly because of different criteria and sampling effort (Pyšek & Prach 1993, Delisle *et al*. 2003, Lavoie & Dufresne 2005), they at least provide collection dates and geographical locations to estimate arrival and establishment of alien plant species. Additionally, they provide an accessible data source for exploring large-scale patterns of plant distributions (Kühn *et al*. 2004, Seabloom *et al*. 2006, chapter 2 & 3, this thesis).

4.2 General characteristic of the study area

There are few areas of the world that are comparable in their ecosystem diversity to Chile. It extends as a narrow belt of land 4,270 km long comprising a broad North-South latitudinal gradient, covering an area of approximately 756,626 km^2. Continental Chile extends between latitudes 17° 30′ and 56° 30′ S and longitudes 68° and 72° W (Figure 1). Administratively, the country is divided into 50 provinces (ranging from 582 to 67,813 km^2 in extent), sequentially ordered from North to South (Figure 1). This arrangement is closely correlated with increasing precipitation and decreasing temperature with increasing latitude (di Castri & Hajek 1976), establishing a smooth gradient in climatic conditions and an orderly sequence of biomes, from extreme desert in the North, a central Mediterranean climate region to temperate rain forest and cold sub-Antarctic wetlands in the South (Figure 1).

Biogeographically, the presence of the Andes Range to the East, the Atacama Desert to the North, and the Pacific Ocean to both the West and South imposes effective biogeographical barriers that have kept the Chilean biota relatively isolated from that of the rest of South America (Arroyo *et al*. 1999). For this reason Chile is considered a continental island, and a part of the territory (i.e. Mediterranean and temperate rainy region) is identified as a hotspot of global biodiversity, due to its remarkably high levels of endemism and biogeographic isolations (Cowling *et al*. 1996).

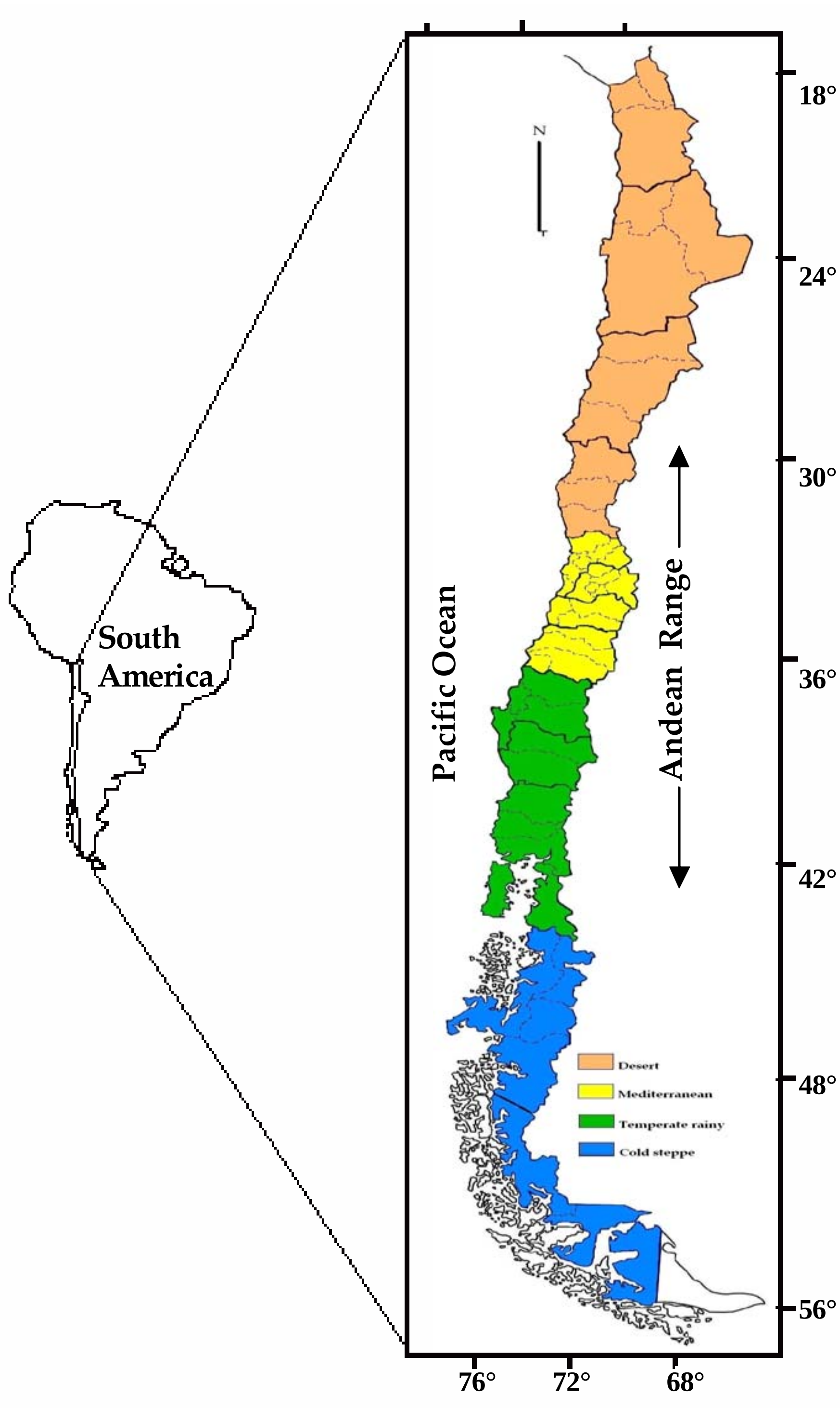

Figure 1. Geographic location of continental Chile. (Source: Köppen climate types, Militar Geographic Institute 1994). Provinces are apportioned to different climate zones ranging from desert (North) to cold steppe (South).

The vascular flora of Chile is composed of 59 orders, 179 families, 813 genera, and about 4,333 native species (Marticorena & Rodriguez 1995, 2001), with a high degree of national and local endemism (Axelrod *et al*. 1991, Arroyo *et al*. 1999, Myers *et al*. 2000). Close to one-half of all native vascular plant species are endemic in Chile (Marticorena 1990), and 47% of vascular plant species are endemic into the Mediterranean region of the country. In the temperate rain forests, around one-third of all genera and two plant families are endemic to this Chilean phytogeographic region (Arroyo *et al*. 1996), with many monotypic genera.

4.3 Susceptibility of Chile to the invasion of alien plant species

The susceptibility of plant communities to plant invasions can be influenced by many factors, such as species composition, community structure, and site resource (Levine *et al*. 2002). The degree of invasion of one community will be a product of its intrinsic susceptibility and extrinsic factors (e.g. level of disturbance providing habitat for alien plants, propagule pressure). Intrinsic susceptibility will be determined by the ability of a resident flora to prevent incoming aliens, a feature that is termed biotic resistance *sensu* Simberloff (1986). The capacity to outcompete aliens may be related to overall richness and diversity, and the flora's potential to promote native colonizing species capable of occupying disturbed habitats (Levine & D'Antonio 1999).

Given that Chile can be considered a continental island (Jaksic 1998, Arroyo *et al*. 1999), and has been strongly isolated from other areas of the South America (Arroyo *et al*. 1996, Armesto *et al*. 1998), the susceptibility of Chile to invasions by alien plants has been associated with the following features:

- The island syndrome of Chile (mentioned above).
- The native flora of Chile has developed relatively few native plants capable to compete with more aggressive plants, e.g. Eurasian species (di Castri 1989), and does not have the potential to generate native species capable of colonizing disturbed habitats (Matthei 1995, Sax 2002). For instance, the Chilean flora lacks native annuals species with strong colonizing ability (Arroyo *et al*. 2000), which

make the country more susceptible to alien plant invasions, given the strong representation of annuals among alien species in general.

- The historical absence of natural disturbance regimes like fire in Chile, and/or the historical presence of fire in other regions of Mediterranean type climate, which are the predominant sources of alien plants in Chile, has favored alien plants which may be better adapted than the local flora to a disturbance regime (Sax 2002).
- The high degree of anthropogenic disturbance on the native ecosystems, which increases the chance of establishment of alien plants species (Arroyo *et al*. 2000, Figueroa *et al*. 2004).

4.4 Composition of the alien flora in Chile

The principal sources of alien plants in Chile are Europe and Eurasia; with 60% of total alien plant species coming from these regions. Other important sources of alien plants for Chile are the rest of South America with 15% of the total, North America and the subtropical regions of Central America with 14% of the total. Other sources such as Africa, Australia, and New Zealand have each contributed with less than 5% of the alien flora (Ugarte *et al*. in press).

The percentage of European and Eurasian alien plants species in Chile (60%) is slightly higher than the average (58.9%) of twenty-six alien floras evaluated around the world (Pyšek 1998). The higher percentage of European and Eurasian species in Chile may be due to several attributes: (*i*) These species possess traits associated to invasiveness, which allowed them to spread quickly (di Castri 1989) in Chilean ecosystems during the last 450 years, (*ii*) the historical use of land in Chile may have allowed for a higher invasibility of local community (Aronson *et al*. 1998, Arroyo *et al*. 2000), and (*iii*) European and Eurasian plants presented higher arrival rates and larger species-pool than plants of other origins due to historical travel and trade routes (Montenegro *et al*. 1991, Figueroa *et al*. 2004, Ugarte *et al*. in press), and thus native communities were exposed to a higher number of plants from these origin. The preponderance of alien plants from European and Eurasian origin in Chile reflects a strong initial contact between Chile and the Old World, mainly due to the Spanish colonizers (Aronson *et al*. 1998), and latter introduction of alien plants from European institutions for human uses (Philippi 1882, Castro *et al*. 2005).

4.5 Evaluation and management of risk invasion in Chile

Because of economic, environmental, and human health costs of alien plants and other invasive species, the Conservation on Biodiversity (CBD) exhorts the contracting parties to "*prevent the introduction, control or eradicate those alien species which threaten ecosystems, habitats or species*" (Glowka *et al*. 1994). Excluding all further plant introductions would most simply safeguard against plant invasions, but that would be neither practical nor legal under current World Trade Organization and other international agreements. Thus, predicting which species have a high invasion potential has been a long-standing goal of ecologists (Kolar & Lodge 2001, Küster *et al*. 2008). This knowledge should be translated into risk assessment schemes that attempt to predict the behavior of alien species in given areas (Daehler & Carino 2000).

If only a small proportion of introduced species becomes invasive (Williamson & Fitter 1996), a risk assessment with given error rate will misclassify and exclude many non-invasive species for every invasive species whose introduction it prevents. This may explain why many countries have not implemented risk analysis for alien plants introductions (Keller *et al*. 2007). However, any risk-reduction strategies applied to the imports of alien plants species produce net economic benefits (Keller *et al*. 2007). In response to the need for a publicly acceptable risk assessment system to predict the invasive potential of plants being considered for importation, screening models such as the Weed Risk Assessment system (WRA, Pheloung *et al*. 1999) have been developed, implemented, and successfully tested across varied geographies, to be adopted as an initial screen for plant species proposed for introduction to a new geography (Gordon *et al*. 2008, chapter 4, this thesis).

Many of the alien plant species in Chile became important agricultural crops, and others did not significantly affect either agriculture or natural habitats (Matthei 1995). In contrast, approximately 60 alien plants have become serious weeds of agriculture (Matthei 1995), and others have invaded natural habitats and replaced the native vegetation (Arroyo *et al*. 2000, Peña *et al*. 2008). Nevertheless, little is known about the invasive potential of the alien plants already present in Chile, as many species may not have been in the country long enough to naturalize and become invasive (chapter 4, this thesis). Additionally, there is no information about the risk of new introductions coming from neighboring countries. Currently, there is a lack of an integrative method to deal with new alien plant introductions, control or management in the territory (Pauchard *et al*. 2004).

5. Objectives and structure of this thesis

The aim of the current investigation is not only to improve the knowledge on the invasions of alien plant species in Chile but also, moreover, to determine the main potential drivers of this process and to assess the risk of new plants introduction and invasion. An additional goal is to contribute to the management of invasive alien plants species already introduced in Chile, assessing quantitatively the priorities for their control or eradication, employing an objective method. Thus, I aimed to address the following issues:

First, I aimed at knowing the history of alien plant introduction into the Chilean territory. I used the herbarium records as historical information of the past introduction plants to answer the following questions:

1. What is the introduction history of alien plants species in Chile?
2. Which were the main driving forces of the introduction process and its subsequent spread?
3. How useful are herbarium records in reconstructing the introduction of alien plants species in Chile?

Second, I aimed at studying how human disturbance together with socio-economic activities are related with the current alien plant species abundance, taking into account the wide climatic gradient of Chile. To accomplish this goal I followed the next questions:

1. Which are the current drivers of alien plant species abundance at province scale in Chile?
2. Do the drivers effects on alien plant abundance change along the wide climatic gradient in Chile?

Third, I aimed at evaluating the current and future risks of alien plant species invasion in Chile. I accomplished this goal following the next questions:

1. Which country, Chile or Argentina, can be a source of a higher risk for its counterpart in terms of new introduction plants?
2. Can be the alien plant risk assessment between Chile and Argentina used as a baseline to establish eradication and control priorities for alien plants species occurring in Chile?

Chapter 2

Alien plants in Chile. Inferring invasion periods from herbarium records

Nicol Fuentes, Eduardo Ugarte, Ingolf Kühn & Stefan Klotz

Biological Invasions (2008), 10(5): 649-657

Abstract

We used 71,764 specimens (14,988 alien and 56,776 native) from the herbarium CONC at Universidad de Concepción, Chile to identify alien invasion periods. We assumed that the pattern of accumulation of specimens can be used for tracing back the distribution in time of alien species introductions in the Chilean territory. To assess this we constructed Invasion Curves (IC) of native and alien species and specimens recorded in the complete territory and we adapted this methodology to draw Proportion Curves (PC). Increments in the proportion of alien vs. native species can be interpreted as expansions in population size of alien species, either locally or by invasion of new areas. To visualize surface expansions consistent with changes in PC we arranged four maps broadly coincident with inflexions in PC: before 1900, 1940, 1980 and 2004. Invasion curves from both native and alien species produced a first step of positive and rapid increment followed by an extended, apparently stable phase. The first expansion phase of alien flora (1910 to 1940) coincides with a first period of strong growth of Chilean agriculture as indicated by increments in wheat and other cereals production. A more recent second maximum showed by PC (approximately between 1980 and 2000) occurs in a period when: (*i*) wheat surface goes down but (*ii*) wheat production increases, and (*iii*) forestry exports increases. These changes are coincident with increased mechanization making possible more wheat production in fewer surfaces. The expansions of alien plant species in Chile are evident on geographical distribution maps. In only one century alien species expanded to nearly all the territory. Both the North and South extremes however, seem to be an exception to this general trend as shown by the gaps on maps.

Introduction

The effects of human-caused biological invasions threaten efforts to conserve biodiversity (di Castri *et al*. 1990, Vitousek *et al*. 1997b, Mooney & Cleland 2001). Thus, learning to identify plant species invaders could reveal the most effective means to prevent future invasions (Sala *et al*. 2000). In this context, data stored in herbarium labels is at present the main source of historical information available about alien plant species in a given zone. Herbarium records are heterogeneous in terms of locations and habitat descriptions (Pyšek & Prach 1993, Delisle *et al*. 2003, Lavoie & Dufresne 2005), but they at least provide us with collection dates and geographical location to approach arrival and establishment of alien species.

Herbarium data has been widely used to study plant invasions (e.g. Pyšek & Prach 1993, 1995, MacDougall *et al*. 1998, Stadler *et al*. 1998, Mihulka & Pyšek 2001, Lienert *et al*. 2002, Delisle *et al*. 2003, Lavoie *et al*. 2003, Willis *et al*. 2003, Gimaret-Carpentier *et al*. 2003, Mandák *et al*. 2004, Wu *et al*. 2004, Lavoie & Dufresne 2005). Pyšek and Prach (1993) prepared invasion curves methods (IC) for reconstructing the propagation history of four alien species in Czech Republic. They adjusted an exponential model to the accumulated number of locations against time. The slope of the corresponding regression line was used as a measure of the invasion rate (Mihulka & Pyšek 2001). Abrupt inflexions on the invasion curve would indicate expansion periods of the alien species involved (Pyšek & Prach 1993).

Later Delisle *et al*. (2003), aiming to account for variability in sampling effort, employed proportion curves (PC). They used proportions of accumulated locations of alien species on accumulated locations of native species. Increments in the proportion of alien vs. native species can be interpreted as expansions in population size (either locally or by invasion of new areas). A faster than normal accumulation of alien herbarium specimens associated to specific locations is interpreted as an invasion period (Delisle *et al*. 2003).

Chile is identified as a hotspot of world biodiversity (Ormazabal 1993) due to its remarkable high levels of endemism and biogeographic isolation (Myers *et al*. 2000), raising concerns on its susceptibility to invasions (Arroyo *et al*. 2000). However, little is known about the history of introductions and fluctuations of abundance of alien plant species. They have been reported in Chile since colonial times in the 16th century (Arroyo *et al*. 2000, Figueroa *et al*. 2004) but they have not been systematically recorded up until the 18th century (review and references in Figueroa *et al*. 2004).

In this research we aimed to identify alien plant species invasion periods in Chile using herbarium records. In order to do that, we accept that the pattern of accumulation of specimens can be used for tracing back the distribution in time of alien species introductions.

Methods

Data source and Analysis

We used an extensive database of 71,764 specimens (14,988 alien and 56,776 native) from the herbarium database at Universidad de Concepción (CONC, founded 1924). Total numbers of species and specimens collected in Chile (hereafter-sampling effort) were plotted against time in ten years periods. A Kendall's rank correlation procedure was used to correlate the number of alien and native species and specimens. Chi-square Goodness of Fit (Sokal & Rolf 1992) was employed to test for differences in sampling effort distribution.

We modified the procedure in Pyšek & Prach (1993) for constructing invasion curves (IC) of native and alien species and specimens. We plotted the cumulative number of species and specimens collected in Chile against time in ten years periods. Pyšek & Prach (1993) reconstructed the invasion history of four species using dates and locations. While we used instead specimens for invasion curves of the total of species and for the whole country. We assumed that the curve for native and alien species reflect the spatio-temporal sampling distribution of herbarium specimens. In other words, we expected that specimen's accumulations of native and alien in a collection should follow the same tendency. As in Mihulka & Pyšek (2001), the slope b of the regression line of the logarithms of cumulative number of species on time was used as a measure of the invasion rate. Differences between alien and natives due to a faster rate of accumulation of alien than the "normal" for natives indicate an invasion period. A t-test of parallelism of regression lines (Sokal & Rohlf, 1992) was employed to test differences between the slopes of alien and native species and specimens.

Also we adapted the methodology in Delisle *et al*. (2003) to draw proportion curves (PC). We divided the cumulative numbers of alien species by cumulative numbers of native species. The proportion obtained was then plotted against time in ten years periods. As for IC, we modified the procedure in Delisle *et al*. (2003), constructing PC for the total species number and not for a reduced set. Then we searched for inflexions corresponding to periods when alien species were more collected than natives. It is worth to note that our PC was constructed using species number and a not specimens as in Delisle *et al*. (2003). Increments in the proportion of alien vs. native species are interpreted as expansions in population size of alien species, either locally or by invasion of new areas, (Delisle *et al*. 2003). This process should result in a faster than normal accumulation of alien herbarium specimens, over those of native species, thus accounting for an invasion period.

To visualize expansions in area consistent with changes in PC we arranged four maps broadly coincident with inflexions in PC: before 1900, 1940, 1980 and 2004. Sampling locations and collection dates for the alien plant specimens were obtained from herbarium labels and processed with a geographical information system (ArcView GIS 3.2, ESRI, USA).

Results

A total of 71,764 herbarium specimens (14,988 alien, 56,776 native) were examined in this study corresponding to 629 alien and 1,997 native species. Eventhough the distribution of sampling effort for alien and native species were significantly different ($\chi^2_{(1,9)}$ = 38.14; P < 0.001), both were positively correlated (Kendall`s-Tau = 0.818; P < 0.001). Most of alien species were collected between 1920 and 1940 (Figure 1a) and during the decades of 1960 and 1990. The vast majority of native species were also obtained between 1920 and 1940 (Figure 1a), but diminished during the 1950 decade and incremented again in 1960.

Sampling efforts for native and alien specimens were significantly different on the last 90 years (Figure 1b) ($\chi^2_{(1,9)}$ = 52.75; P < 0.001). However, both were positively correlated (Kendall`s-Tau = 0.745; P < 0.001). Variation in sampling effort, in species and specimens, is evident when examining shorter periods. For instance, during the

1930 decade 400 native species were recorded (Figure 1a) from near 2,000 specimens (Figure 1b) while for the year 2000 from approximately 8,000 specimens only 60 species were registered. Similar tendency is evident for alien species, during the 1930 decade 100 species (Figure 1a) in 800 specimens were obtained (Figure 1b), while during the year 2000, 50 species were recorded on 2,000 specimens.

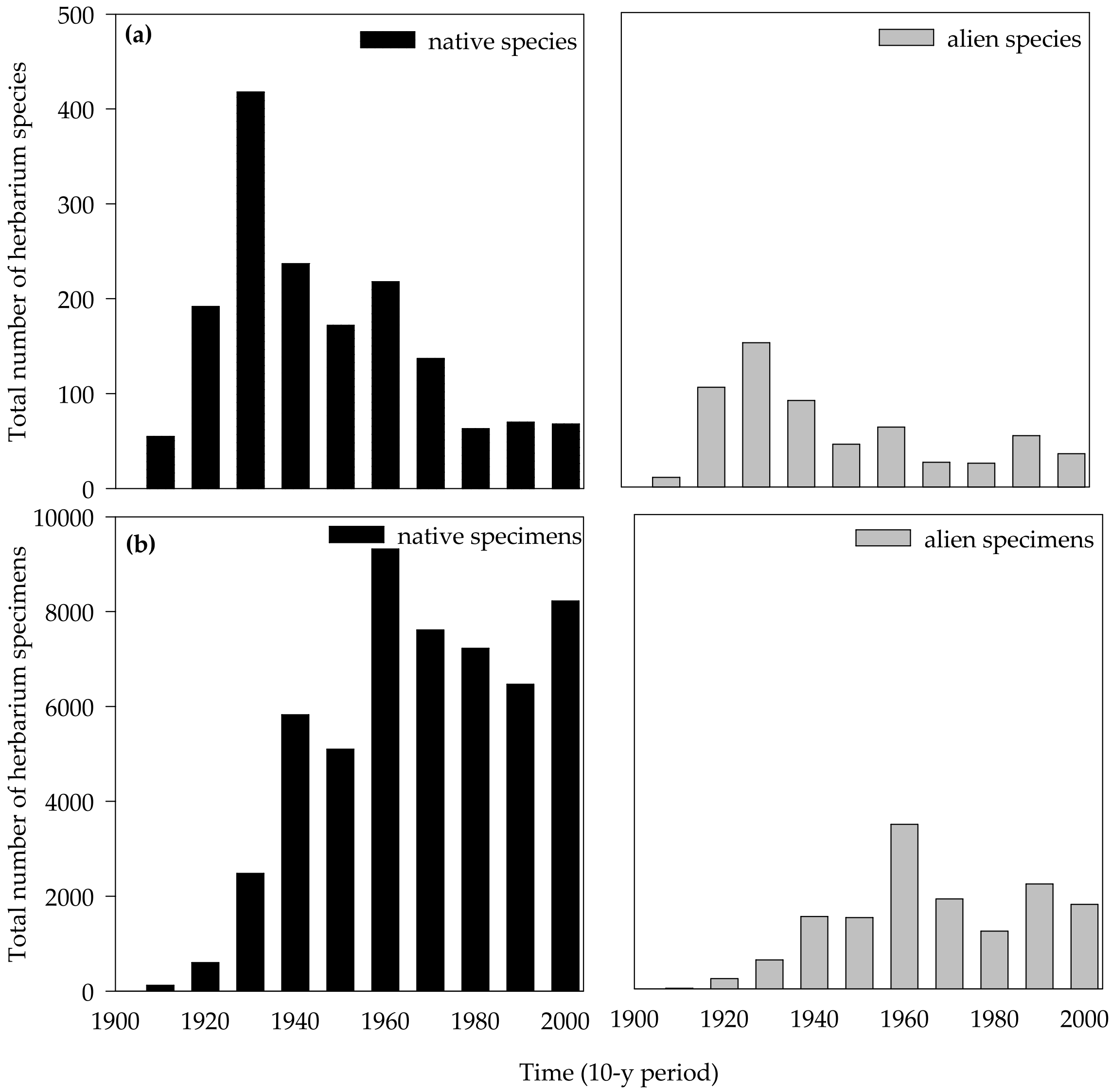

Figure 1. Total number of herbarium species (a) and specimens (b) recorded in the Herbarium of the Universidad de Concepción, Chile (CONC) plotted against time (10-year periods).

Slopes of IC for alien species (Figure 2a) and specimens (Figure 2b) did not differ significantly from that of native species and specimens respectively, suggesting similar rates on species accumulations. However, IC for alien species and specimens shows a notorious increment between 1910 and 1940 (Figure 2a; 2b). The same inflexion was evident on PC (Figure 3) between 1910 and 1940. During that period the predominant families collected were Poaceae, Asteraceae and Fabaceae (Figure 3, inset). Additionally, a second period of increment is evident on PC (Figure 3) from 1980 on. However, this is of lower magnitude as compared with the first one.

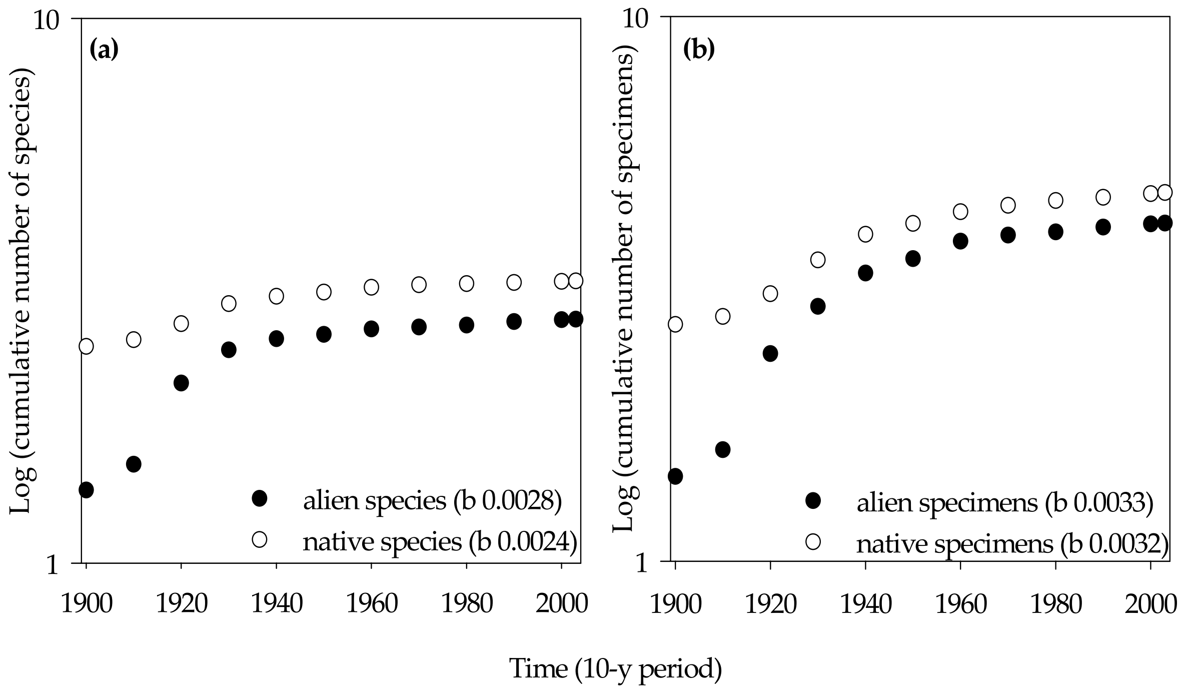

Figure 2. Invasion curves (*sensu* Pyšek & Prach 1993) for alien and native species (a) ($P > 0.01$; $R^2 = 0.89$; $R^2 = 0.91$ respectively; $P = 0.08$ test of parallelism) and for alien and native specimens (b) ($P > 0.01$; $R^2 = 0.96$; $R^2 = 0.97$, $P = 0.16$ test of parallelism). Invasion rate (slope *b*) is given for each alien and native species and specimens. Records were obtained from Herbarium of the Universidad de Concepción, Chile (CONC).

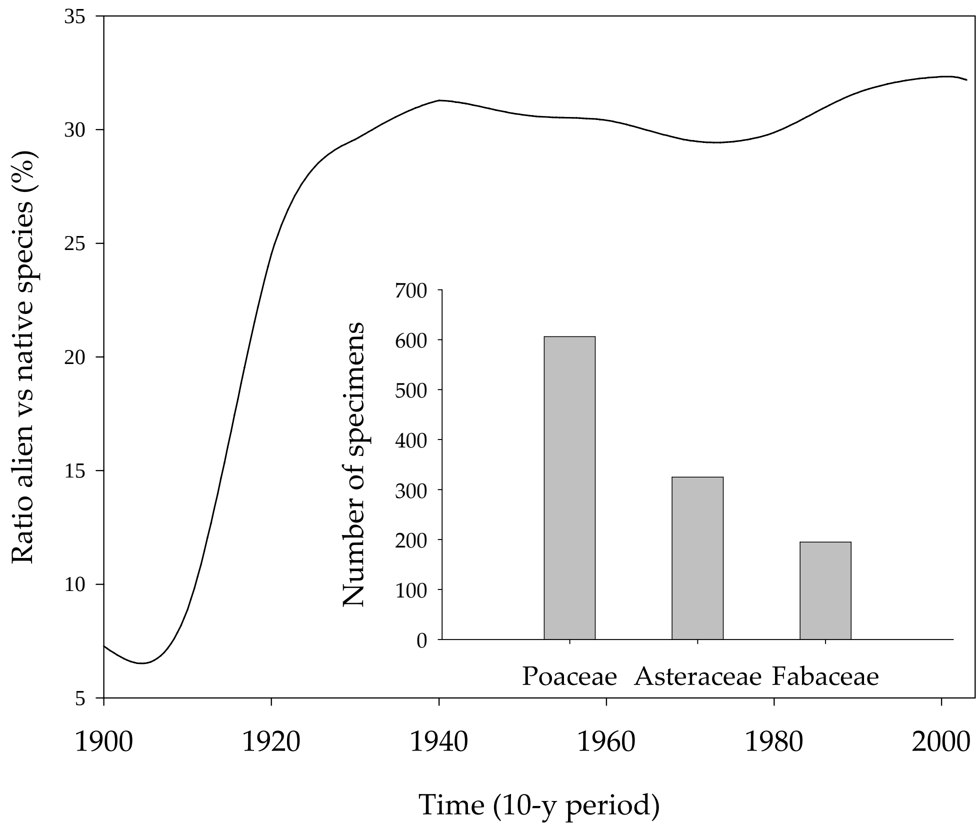

Figure 3. Proportion curve (*sensu* Delisle *et al.* 2003) i.e., cumulative number of alien species divided by cumulative number of native species in Chile, calculated for every 10 years intervals. Proportions obtained were then plotted against time. Inset Family with more alien specimens in the period 1910-1940. Records were obtained from Herbarium of the Universidad de Concepción, Chile (CONC).

To broadly visualize the spatial dimension on alien expansion in Chile 13,827 specimens were used to prepare distributions maps (Figure 4). They are presented in four steps. First, before 1900 (Figure 4) 28 specimens were collected only in the Mediterranean climate in central Chile. By 1940 it reached 2,300 specimens (Figure 4), most of them from the central Mediterranean zone but incorporating some exemplars from north and south extremes. Subsequently, towards 1980, a proportionally large number of alien specimens are added to reach 10,478 (Figure 4) with a significant increments in area. Again, they are concentrated on the Mediterranean central zone but now with a significant participation of exemplars collected on the temperated rainy forest, southern from the Bio-Bio river; also extremes North and South increment noticeably. Lastly, by 2004 it reaches 13,827 specimens (Figure 4) without noticeable increments in the area covered, suggesting stabilization or “saturation”. From a broad perspective, both the northern and southern portions exhibit areas of significant size without records (Figure 4). They broadly correspond to the Atacama Desert on the north and to ice-covered areas on the south.

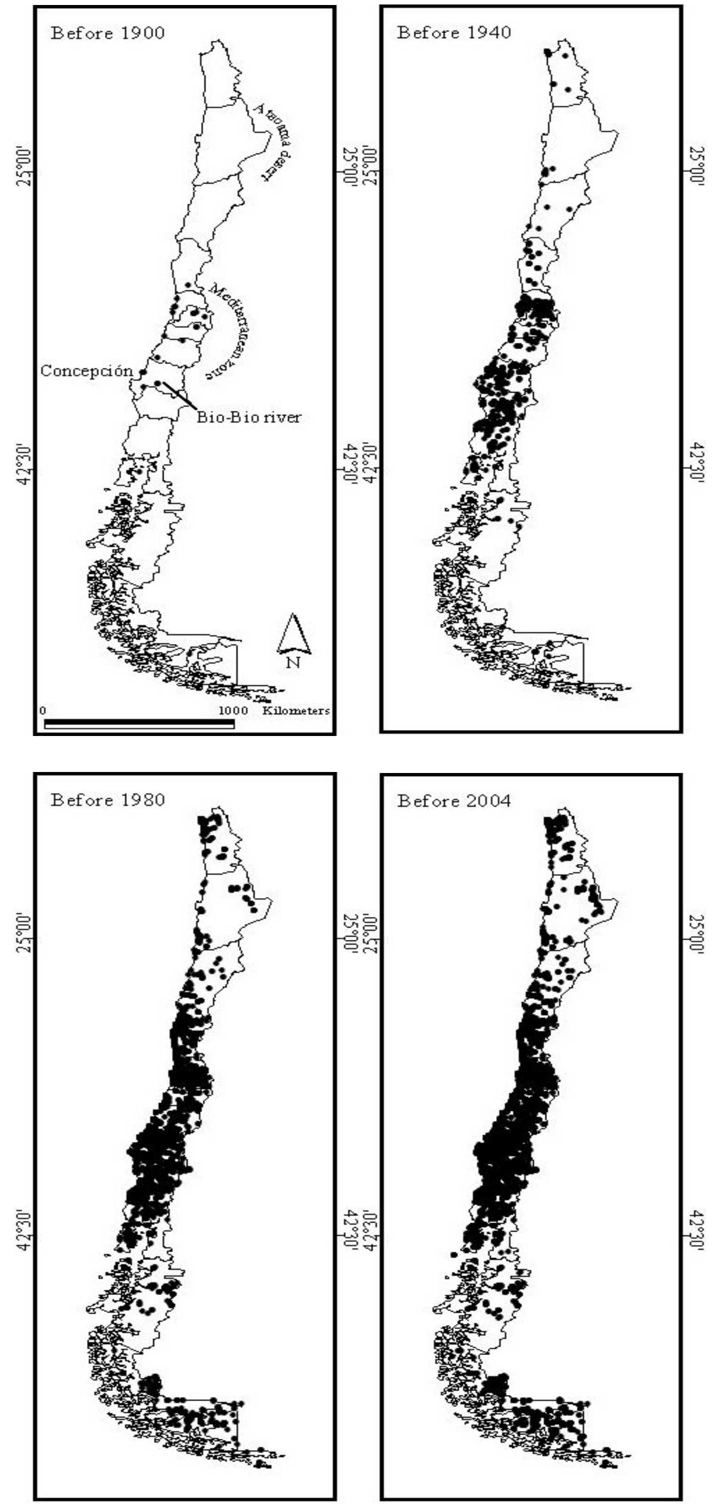

Figure 4. Location of alien specimens (black dots) with place names cited in the text- collected before 1900 (28), 1940 (2,300 specimens), 1980 (10,487) and 2001 (13,827) respectively. Sampling locations and collection dates were obtained from Herbarium of the Universidad de Concepción (CONC), Chile.

Discussion

We identified invasion periods of alien plant species in Chile from the collection dates of specimens deposited on CONC herbarium in Concepción Chile. We corroborate that alien species and specimens accumulate in relation to alien species introductions into new areas. Undoubtedly, herbaria are at the present times the one of the most reliable source of information to document past changes in a given flora. The more than 70,000 well-checked specimens used in this study should be sufficient to diagnose the situation in Chile in the past and for the evaluation of future risks.

We adapted invasion and proportion curves by Pyšek & Prach (1993) and Delisle *et al*. (2003) respectively and used them with full collections and specimens, and not only for a reduced group of species and their localities. We acknowledge all known "drawbacks" and peculiarities of information registered on herbarium labels mainly in terms of the quality of habitat description and geographical distribution (Wu *et al*. 2005). But also we accept that having a location, a date of collection and well-checked taxonomy should grant the use of that information to inquire on the accumulation process and, by it, on the dynamics of establishment and expansion of aliens in Chile.

Additionally, we accepted that the accumulation of native specimens corresponds to a "normal", expected situation for increments on a collection. We are also assuming that, first, there is a definite pattern and, second, that both native and aliens follow the same pattern of accumulation. Consequently, by comparison of both, it is possible to detect changes in the rates of accumulation of species evidencing periods of increments of new species into the flora.

When accumulated as IC, both native and alien species produced a first step of positive and rapid increment followed by an extended, apparent plateau phase. Steep increments on the first phase of IC for native species are related with increments in floristic sampling intensity (associated to the foundation and increments in collection efforts at CONC in our case) and, in part, to higher levels of floristic richness and endemism in the Mediterranean climate region in central Chile (Myers *et al*. 2000). Delisle *et al*. (2003) argue that this initial phase in the native species represent the history of the state of knowledge of the range occupied by these species. Both, species and specimens levelled off and follow a similar pattern from 1940 on. Also, it is evident the lack of collections before 1900. Moreover, a second inflexion not present in IC was evident in the PC curve. Since PC is constructed using a proportion (alien vs. native species), it should be more responsive to changes in alien flora. For a curve of natives increasing to some sort of normal rate, any unusual increase or leap of alien species would result in an inflexion on the curve. Also, alien vs. natives proportions cancel out the effects of fluctuations in year to year sampling effort. We assume that there is no bias towards any of both natives or alien species and they accumulate independently.

The first expansion phase of alien flora (1910 to 1940) coincides with a first period of strong growth of Chilean agriculture (Cariola & Sunkel 1982) as indicated by increments by wheat and other cereals production (Figure 5). Also Matthei (1995) reports on sustained increments in the collection of weeds from 1894 to 1934 (100 new alien species) associated to wheat imports. Aronson *et al*. (1998) recognizes a “first wave” of species introduction in the drier central Mediterranean climate area starting on colonial times (1880) and ending by early 1920’s, associated to landscape transformations. There is reasonable correspondence between that phase and the expansion phase recognizable between 1910 and 1940 in our results. In general the areas under Mediterranean climate and temperate rainy influence have a well documented history of pervasive human influence, landscape degradation and losses in diversity (Aronson *et al*. 1998, Arroyo *et al*. 2000).

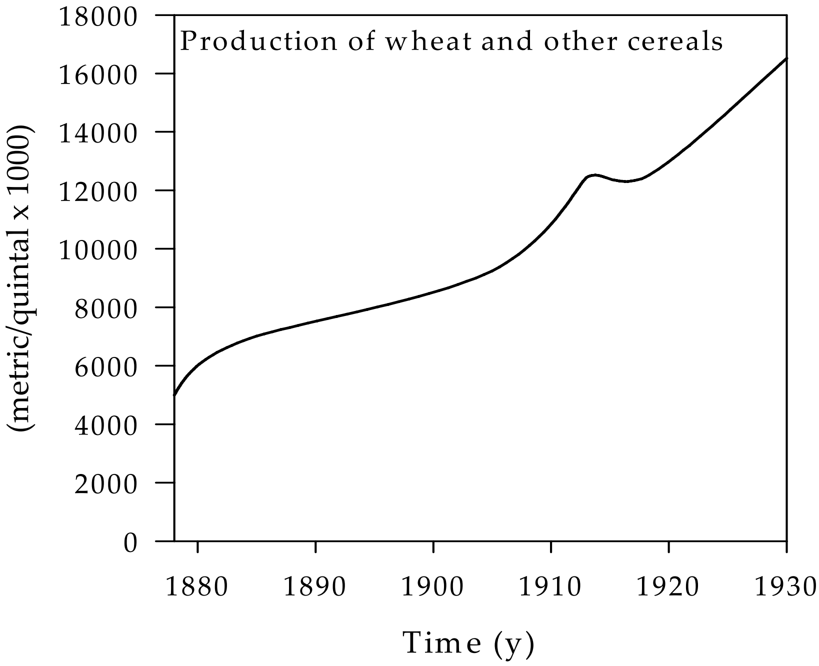

Figure 5. Production of wheat and other cereals (metric/quintal x 1000) in Chile from 1878 to 1930. Data were obtained from Cariola & Sunkel (1982).

In contrast, the more recent second maximum showed by PC (approximately between 1980 and 2000; Figure 3) occurs in a period when: (*i*) wheat surface goes down (Figure 6a) but (*ii*) wheat production increases (Figure 6b) and at same time (*iii*) volume of forestry plantations and forestry exports increases (Figure 7). Those changes are coincident with increased of mechanization that made possible more wheat production in less surface. It is known also that during that period part of the land dedicated to wheat has been changed into forestry plantations. Moreover, Fuentes *et al*. (unpublished data) found non significant relationship between alien species richness and forestry plantations activities, but a significant positive one with agriculture at provincial level. Recent changes in land-use could be then promoting a new phase in alien species arrival and expansion in Chile. That tendency is, with our data, not possible to project for the future.

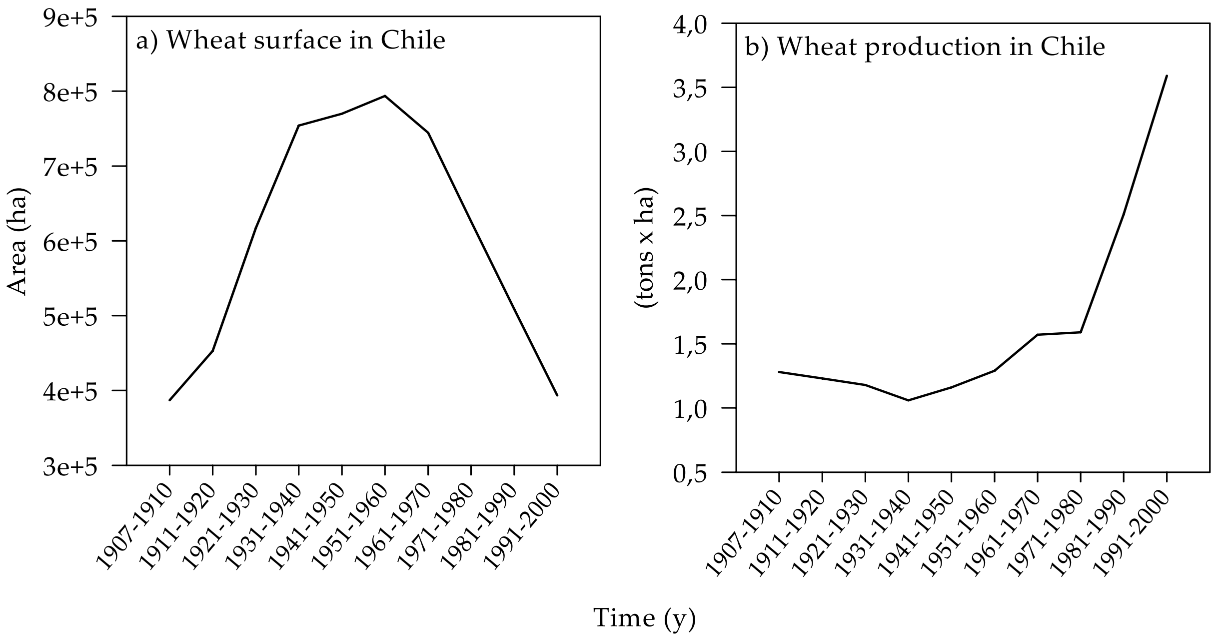

Figure 6. Surface of wheat (ha) cultivated in Chile (a) and production of wheat (tons x ha) (b) data were obtained from Mellado (2007).

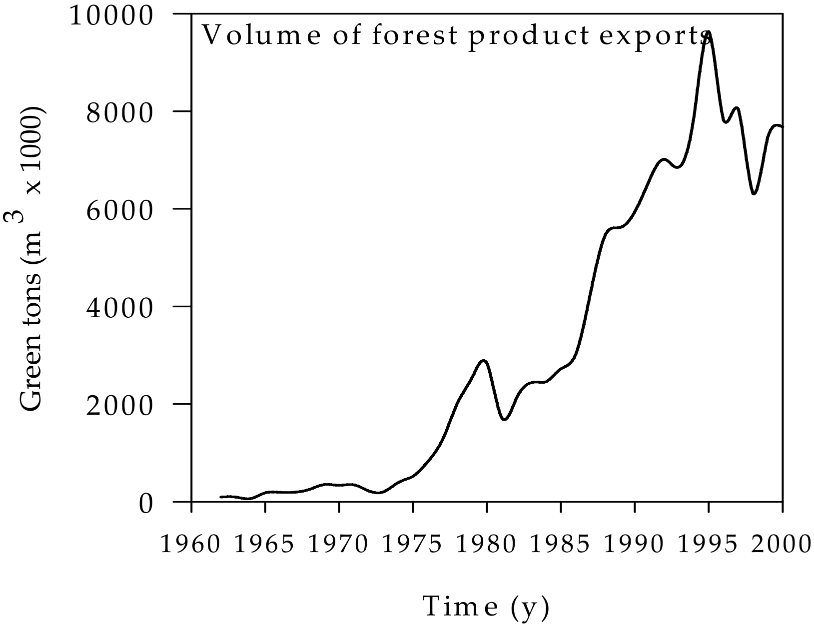

Figure 7. Volume of forestry products exports (Green metric tons), (lumber, pulpwood, periodic paper, elaborate wood, moldings, furniture and chips) in Chile (m^3 x 1000). Data were obtained from Corporación Nacional Forestal and Instituto Forestal (CONAF – INFOR, 2005. www.conaf.cl).

The expansion of alien species in Chile is clearly evident on spatial changes visualized by geographical distribution maps (i.e., the four periods in Figure 4). In only one century alien species expanded to nearly all the territory. Both the North and South extremes however, seem to be an exception to this general trend as shown by the gaps on maps (Figure 4). This can be explained by different circumstances. First, the North has been thoroughly explored and collected during the last three decades and gaps there are then attributable to the harsh hot desert there. Gaps in the southern extreme area could be instead the result of a combination of less intensity in collection efforts due to inaccessibility as well as to the big sections of land covered with permanent ice or natural forest.

Both curves give rise to questions like: How can we understand the curves in historical terms? Are changes concordant with relevant historical events in Chile? It is widely accepted that the spread of native plant species from refuge after last glaciations event ca. 10.000 years ago with different success in terms of colonized area, (Hinojosa & Villagrán 1997). While aliens species have been present only for four and a half centuries (from around 1520 to 2000) when Spanish conquerors brought agriculture to the Mediterranean climate area in Chile. It is important to take into account that the Spanish colonization period embraces two distinct steps in Chile (Aronson *et al*. 1998). (*i*) The Spanish were able to control and settle only the territory located to the north of the Bio-Bio river for three and a half centuries (Aronson *et al*. 1998). (*ii*) Only during the last century the territory was secured for settling southern from the Bio-Bio river. Consequently, for three and a half centuries alien species were restricted to the territory north from the Bio-Bio river. Only during the twentieth century the whole Chilean territory was open for alien species to establish and disperse, when clearing of the southern temperate forest was massive and intensive (Donoso 1996). The difference on the first phases of IC curves then is at least in part explained by the expansion of alien species to the territory southern of the Bio-Bio river when new land was available to them. They could originate from aliens already present north of the Bio-Bio and from new species finding new opportunities under the new temperate rainy conditions, or new ones through new ports opened at the south.

The differentiation of origin should be correlated with present distribution ranges (Fuentes *et al*. unpublished data).

In summary, we identified two periods of increment in alien species in Chile both related to changes in agriculture and forestry plantations. Historically in the first period to phases are confounded: the Mediterranean zone gave aliens opportunities to expand during three centuries while the temperate rain zone has been open only during the last century. There is a second increment suggested by a peak on the PC which could be a response to changes in agriculture and probably to an intensification of forestry plantations activities. Consequences and risks in terms of spreading and invasions of individual species will require to be documented by an efficient combination of herbarium records with well designed, specifically oriented, sampling programs.

Chapter 3

The role of human habitat disturbances and climate gradient on alien plants density at provinces scale in Chile, South America

Nicol Fuentes, Eduardo Ugarte, Ingolf Kühn & Stefan Klotz

under review in: *Basic and Applied Ecology*

Abstract

It is expected that, in conjunction with fast growing economies, and as a result of trade, there may be a consequent increase in the number of alien plants. We examined the density of alien plants in the fifty provinces of Chile and by examining the relationship between alien plants density and two groups of proxies for degree of disturbance related to socio-economic and land-use variables. The data is based on herbarium collections and herbarium data base at the Universidad de Concepción CONC and by using an historical approach using the density of alien plant that relates to: gross domestic product (GDP) per area, density of agricultural land, density of abandoned agricultural land, density of forest plantations, road density and climate types a generalized linear model was developed. This evaluated these selected variables on alien plant density. We tested for spatial autocorrelation and controlled for outliers. Alien plant density from the fifty provinces was positively correlated with GDP ($P < 0.001$), road density ($P < 0.01$), and density of agricultural land ($P < 0.001$), and was inversely correlated with climate type ($P < 0.01$). However, when the outlier provinces (Valparaiso, Santiago, Concepción, and Palena) with high population density were deleted, GDP lost its predictive power, and yet the significance of road density, density of agricultural land, and climate type remained. These variables changed when the analysis was performed separately for each climate type. Alien plant density was greatest in provinces with Mediterranean and temperate rainy climates and declined towards both the northern desert areas and southwards to cooler environments. Areas with low densities of alien plants are those with less degree of human disturbance too.

We show that the level of human activity and climate type directly influence the number of alien plants present in Chile.

Introduction

Economic activities normally result in an increase of ecosystem disturbance, with increased propagule pressure and a subsequent establishment of alien plants (Lonsdale & Lane 1994, Hodkinson & Thompson 1997, Taylor & Irwin 2004). Human population density and per capita GDP, acting as proxies for human disturbance, have been claimed to correlate positively with alien plants density (Dalmazzone 2000, Liu *et al*. 2005). A strong positive correlation was found for alien plants numbers and economic activity (Taylor & Irwin 2004). It is for this reason that high numbers of alien plant species are predicted for areas with fast growing economies, with a subsequent impact on its biodiversity (Cincotta *et al*. 2000, Taylor & Irwin 2004).

Climatic conditions are fundamentally important for an arriving alien (Panetta & Mitchell 1991), because determine the constraints to survival, establishment and reproduction (Panetta & Mitchell 1991, Scott & Panetta 1993). Knowing the tolerance of different species it should be possible to predict distributions. However, socio-economic factors can override the effects of climatic conditions (Pino *et al*. 2005) and climatic similarity alone may not be the only factor enabling an establishment. For example, the rate of spread of the invasive *Heracleum montegazzianum* was similar in two European countries (Czech Republic and UK), with different climate regimes, indicating that environmental constraints imposed in the countries may not be as important as previously presumed (Pyšek *et al*. 2007).

Chile was identified as a hotspot of world biodiversity (Myers *et al*. 2000), on account of a high level of plant endemism and biogeographic isolation (Cowling *et al*. 1996). This has raised concerns on its susceptibility to invasion (Arroyo *et al*. 2000). This southern continental country has one of the most dynamic economies in South America. Areas with higher numbers of alien species are those most disturbed from human population and trade impacts (Matthei 1995, Arroyo *et al*. 2000). Additions of alien plants in Chile were related to developments in agriculture and forestry plantations (Fuentes *et al*. 2008). A preliminary analysis considering only weeds plants and at a broad spatial scale, had a correlated regional (a region involves a group of provinces) alien distribution in Chile according to land uses (Arroyo *et al*. 2000). However, at the regional scale the risk of averaging relevant information increases, and conclusions needs to be considered with caution (Figueroa *et al*. 2004). A better understanding of the criteria that enable colonization of new environments involving human-generated habitat disturbances and climate gradient on alien plant density at provinces scale is needed.

Here we examine the relationship between alien plant density and two groups of proxies for degree of disturbance in provinces in Chile that occupy a wide range of climates from desert to cold steppe. We examine how human disturbance within this wide range of climate, together with socio-economic factors that include: human population density and gross domestic product (hereafter GDP) and land-use variables: density of agricultural land, density of abandoned agricultural land, density of forest plantations, and road density, are related with alien plant density. Also we examine the relationship above mentioned separated into four main climate types in an independent analyses.

Methods

Study area

Chile extends over 40 degrees of latitude, a distance of more than four thousand kilometers from extreme desert in the north, a central Mediterranean climate region to temperate rain forest and cold sub-Antarctic wetlands in the south (Figure 1). For this reason Chile provides a remarkable broad series of climatic and vegetation gradients for ecological studies. The fifty provinces in Chile range from 582 to 67,813 km^2 in extent (Figure 1).

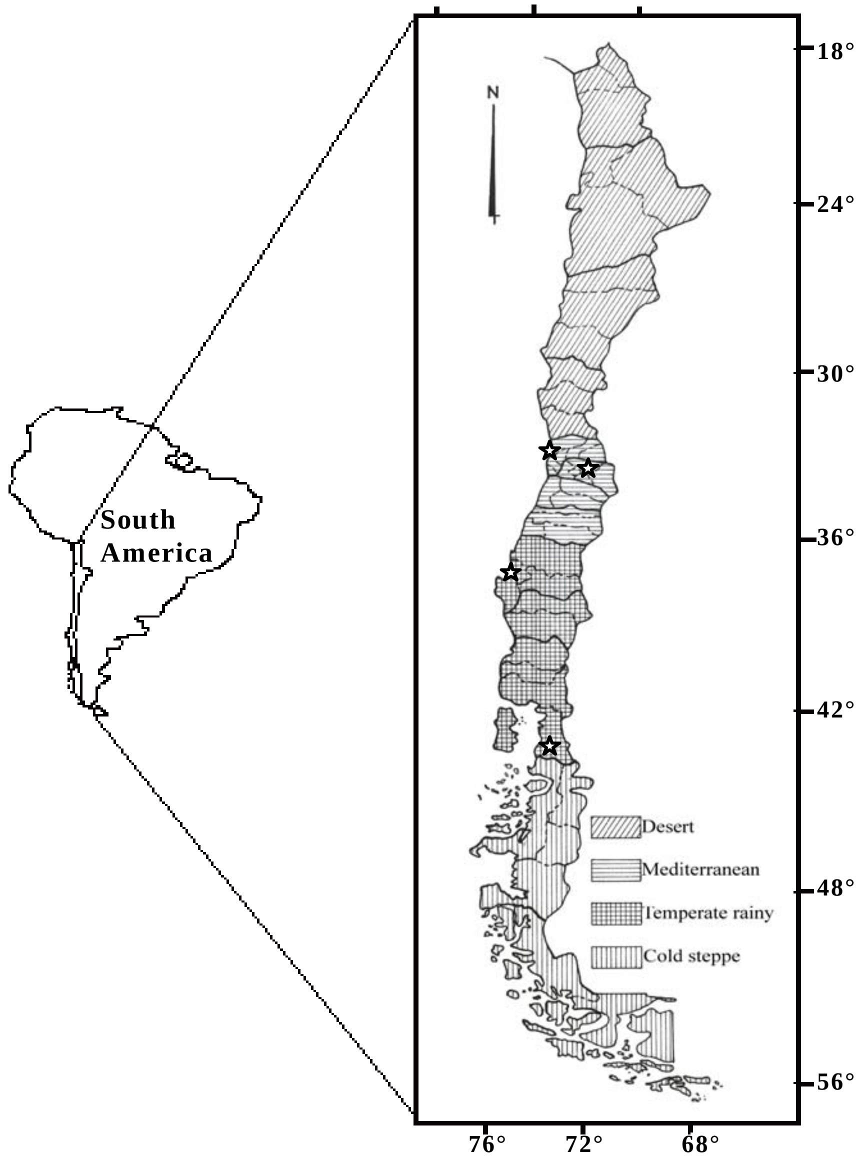

Figure 1. Provinces of Chile apportioned to different climate zones ranging from desert to cold steppe in this analysis. Stars represent provinces outliers from north to south: Valparaiso, Santiago, Concepción, and Palena.

Data source

Numbers of alien plants for each province were derived from a herbarium data base (CONC Herbarium, Universidad de Concepción, Chile). Density of alien plant species per province was obtained by dividing the number of alien plants by the Log_{10} area of each province. This method avoids bias according to the different areas of each province (Lonsdale 1999). Socio-economic variables consist of human population density and GDP per area, and were obtained from the National Statistics Institute

(INE 2002). Land-use variables used were density of agricultural land, density of abandoned agricultural land, and density of forest plantations (INE 2002). The density of roads was obtained from the Department of public construction. The density of forest plantations was evaluated for provinces with Mediterranean, temperate rainy, and cold steppe climate types, there being none in the desert. Each province was classified into one of the following Köppen climate types (Militar Geographic Institute 1994): desert, semi-desert, Mediterranean, temperate rainy, cold rainy and cold steppe.

Analysis

All variables were standardized to zero mean and unit variance. We tested for multicolinearity using a correlation matrix (Sokal & Rohlf 1992). This provided a positive correlation between population density and GDP per area (r = 0.96). We selected GDP for further analysis.

We used backward stepwise regression procedures, based on Akaike Information Criterion (AIC), to determine the best model using the following variables: alien plant density; GDP per area, density of agricultural land, density of abandoned agricultural land, density of forest plantations, roads density, and climate types. Climatic type (categorical variable) was coded hierarchically, which is different from the least squares fitting. In hierarchical coding, the levels of the categorical variable are considered in some order and a split is made to make the two groups of levels that best separate the means of the response. Then each group is further subdivided into its most separated subgroups, and so on, until all the levels are distinguished into k–1 terms for k level (SAS Institute 2000).

A generalized linear model (GLM) was used to evaluate the relative importance of each variable. Given that spatial proximity on provinces may increase the likelihood of autocorrelation, a Durbin-Watson test for autocorrelation (Sol *et al*. 2008) was run on residuals (Seber & Wild 1989). Outliers (Sokal & Rohlf 1992) were detected employing Cook´s D Influence Index (Cook 1977) and deleted in a subsequent run. Their influence on the predicted value was inferred by comparison between both runs.

The whole procedure was repeated for provinces, now grouped according to six climates: desert, semi-desert, Mediterranean, temperate rainy, cold rainy and cold steppe. Due to the small number of semi-desert provinces these were combined with the Mediterranean climate as was the temperate and cold rainy climates to provide four units (Figure 1). On each of them, GLM analyses were performed separately. A first analysis followed by a second one without outliers as before. We performed a one-way ANOVA followed by a post-hoc test to find significant differences on alien plant densities among the six climatic types.

Results

Alien plant density within Chilean provinces was positively correlated with GDP, road density, and density of agricultural land, and was negatively correlated with climate type (Table 1). Cook's D values (range 1.09 – 1.4×10^{-6}) were higher in Santiago (1.09), Valparaiso (0.07), Concepción (0.05), and Palena (0.14). Once outlier provinces were deleted from the regression, GDP alone was not significant as a predictor of alien plant density, whereas road density, density of agricultural land, and climate type were found to be of importance (Table 1). The density of alien plant appears to be directly related to human activities, overriding all other variables. Only two of eight analyses showed a marginal significance for spatial autocorrelation (Durbin-Watson test; P = 0.02; Table 1). For this reason we deduce that our results are robust.

Results according to climate were (Table 1): desert: where the model indicated a positive relationship between alien plant density and density of agricultural land; semi-desert/Mediterranean where GDP was significantly correlated with alien plant density, when all provinces were included. Whereas road density was found to be significantly influenced once the outliers, Valparaiso and Santiago, were removed. All provinces in the temperate-rainy/cold rainy climate grouping showed a significant relationship with alien plant density and both GDP and road density. When the outliers Concepción and Palena were excluded, the GDP was found to be negatively correlated, whereas the density of agricultural land was a significant positive predictor. In cold steppe climate: density of agricultural land showed a significant positive relationship with alien plant density.

Table 1. Partial coefficients of GLM among alien plant density and socio-economic, land-use, and climate types using all fifty provinces and without outliers, forty six provinces. GLM within the climatic types: desert; semi-desert/Mediterranean (with outliers Santiago and Valparaiso); semi-desert/Mediterranean (without outliers Santiago and Valparaiso); temperate-rainy/cold rainy (with outlier Concepción and Palena); temperate-rainy/cold rainy (without outlier Concepción and Palena) and cold steppe. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; n.s. = non significant; n.i. = not included.

	50 provinces	46 provinces	desert 9 provinces	semi-desert/ Mediterranean 22 provinces	semi-desert/ Mediterranean 20 provinces	temperate-rainy/cold rainy 11 provinces	temperate-rainy/cold rainy 9 provinces	cold steppe 8 provinces
Gross domestic product	0.46***	n.s.	n.s.	0.41**	n.s.	0.86**	-6.3**	n.s.
Roads density	0.24**	0.28**	n.s.	n.s.	0.74**	0.57*	n.s.	n.s.
Density of agricultural land	0.32***	0.29**	0.26*	n.s.	n.s.	n.s.	0.85***	0.41*
Density of abandoned agricultural land	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Density of forestry plantations	n.i.	n.i.	n.i.	n.s.	n.s.	n.s.	n.s.	n.i.
Climate type	-0.32**	-0.33**	n.i.	n.i.	n.i.	n.i.	n.i.	n.i.
R^2	0.64	0.61	0.48	0.42	0.19	0.65	0.91	0.49
R^2 adj	0.59	0.58	0.37	0.35	0.14	0.61	0.87	0.41
AIC	-37.6	-44.04	-17.7	-4.5	-9.2	-7.4	-21	-8.7
Durbin Watson test on spatial autocorrelation	0.1	0.3	0.27	0.02	0.02	0.9	0.3	0.5

We found significant differences among climate types for alien plant density (One way ANOVA, $P > 0.001$; $F = 0.35$; Figure 2). Mediterranean and temperate rainy climates had the higher values of alien plant density. Desert vs. temperate rainy and cold steppe vs. temperate rainy were significantly different (Tukey test; Figure 2).

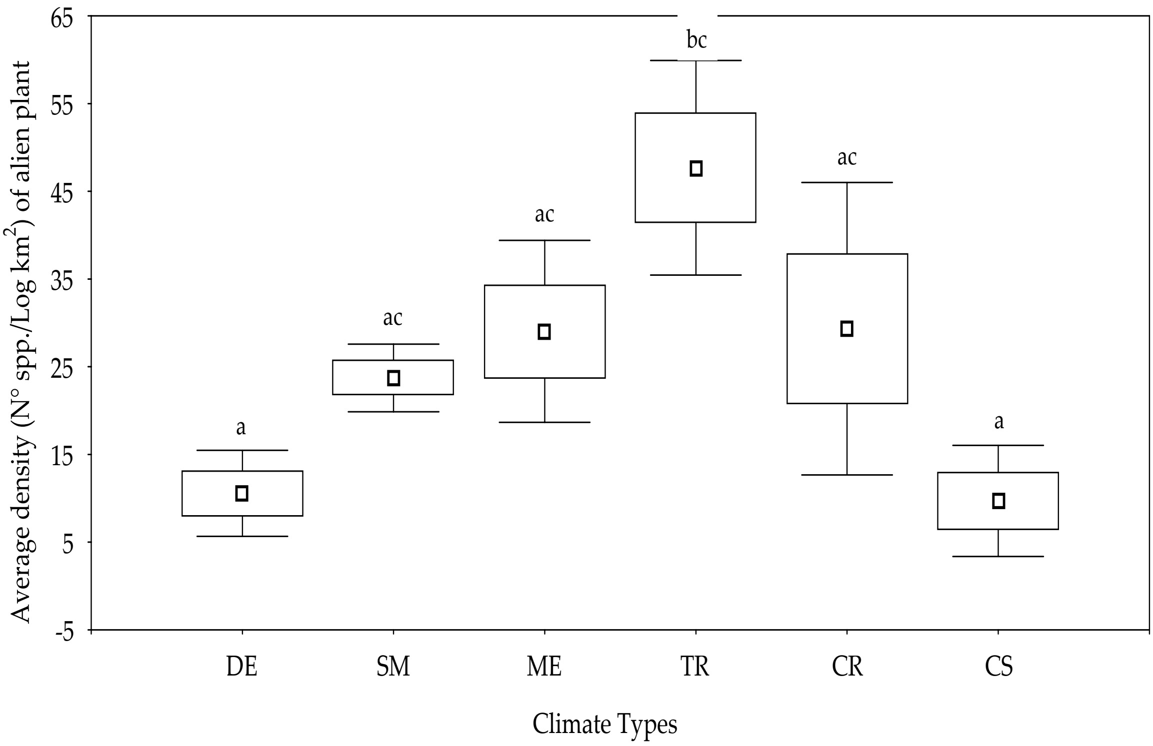

Figure 2. Results of one way ANOVA, average densities (Nº/Log_{10} (km^2) ± SE) of alien plant species per climate regions. Solid squares are medians, boxes are standards error, and whiskers are standards deviations. DE = desert; SM = semi-desert; ME = Mediterranean; TR = temperate rainy; CR = cold rainy, and CS = cold steppe.

Discussion

The density of Chilean alien plants was related to disturbance and economic activities. Also the GDP was correlated with alien species density when tested for all provinces. However, after deleting the four outlier provinces, road density, density of agricultural land and climate type were the best predictors of alien plants density in Chile.

In macro-analyses of this nature, inequities in GDP distribution (or surrogates) can generate sampling bias (Westphal *et al*. 2008). For example, the provinces with higher GDP have more or better mapping schemes. Under these circumstances the extreme values from outliers drove the model (Westphal *et al*. 2008), in our case, towards a positive and apparently robust role as predictor of alien plants density. As reported in Westphal *et al*. (2008), when GDP outliers are removed from the analysis, a different result emerges as was the case for four Chilean provinces: Santiago, Valparaiso, Concepción and Palena. The first three are densely populated, consisting of the greatest share of the country's GDP. While Palena, has one of the lowest GDP with a low human population. In this context, results of previous macro-analyses, that found a strong effect of GDP (or surrogates including GDP), on alien plant richness (Liu *et al*. 2005) and alien plant density (Vilà & Pujadas 2001), suggested that a different picture can arise should the data be re-analyzed taking into account those outliers that bias the results.

We found road density and the density of agricultural land were independent and positive predictors of alien plant density. A previous study, at the regional scale (i.e. thirteen regions in Chile), reported insignificant effects for agricultural land, but a positive one for road density for weeds distributions in Chilean regions (Arroyo *et al*. 2000). We believe that there are two reasons why these results differ from ours. In our study we examined all Chilean provinces (fifty in total) whereas Arroyo *et al*. (2000) examined regions (thirteen in total), which is a broad spatial scale. We also specifically tested the influence of outliers and spatial auto-correlation. Both of which strongly influence results (Sol *et al*. 2008), or bias model adjustment (Westphal *et al*. 2008).

Agricultural land is of particular importance for the dispersal of alien plants which following arrival has enhanced opportunities for colonisation (Mack 2000). Many plants were introduced as agricultural crops over the past century in Chile, and as a result, many agricultural weeds, often introduced as contaminants with imported seed become introduced (Matthei 1995). Additionally, Fuentes *et al*. (2008) suggested that the first increase in the rate of alien plant arrivals (1910-1940) was associated with the expansion of Chilean agriculture. The positive relationship of road density and alien plant density may also be caused from propagule pressure seeding beside roads

(Trombulak & Frissell 2000). Recent evidence would confirm that this is a significant factor for the dispersal of alien plants into protected areas (Pauchard & Alaback 2004) and links the exchanges of alien plants between Chile and Argentina (Fuentes *et al*. 2008 unpublished data).

What was unexpected was the non-significance of forestry plantations on the density of alien plants. Although Fuentes *et al*. (2008) predicted that forestry operations would also result in contributing to the increase in the rate of arrivals. Forest plantations are concentrated within the southern provinces in Chile. These provinces with high levels of wood production should be examined further. We also found that agricultural fields that were abandoned were unexpectedly not significant on alien plant density. This contrasts with the presumed situation where such areas may act as reservoirs for alien plants and their propagules and so spread to neighbouring areas (Burke & Grime 1996, Mack 2000) and a much higher source pool than the dryer (desert) or cooler (cold steppe) regions.

Alien plant density was greatest for Mediterranean and temperate rainy climates, and progressively lower to the north and south to areas with greater climatic extremes. Also climate types with higher values of alien plants density in Chile coincide with those that have become more disturbed (Montenegro *et al*. 1991, Matthei 1995), and where there were dense populations and in areas with greater economic development. Aliens have been arriving in Chile for more than four centuries with significant arrivals beginning with Spanish colonisation to the Mediterranean region. This climate zone has been under intensive use (Aronson *et al*. 1998), and it would appear that the larger the duration of human disturbance the greater the expected propagule pressure (Fuentes *et al*. 2008).

Contrasts among the dry north, the Mediterranean centre, the temperate rainy and the cold wet south climate types raised the question if the same pattern of correlations, between alien plant density and socio-economics and land-use variables, will still hold when tested on each of the four climate types separated and independently. The relationship changed when outliers were extracted from the regression model. Agriculture-related variables were good predictors of alien plant density in three of the four climate types analyzed, in areas where human population do not concentrates on big urban agglomerations. Only in temperate rainy GDP was significant predictor, but inversely correlated. Clearly, the main source of propagule pressure came from an area of intense agriculture and human population concentrated on big urban centers.

We have shown that provinces with a low degree of human disturbance in northern and southern Chile, that have more extreme climates, have the lowest density of alien plants. Chile is expanding its economy and as a result of finding the greater number of alien plants in areas of human disturbance we would expect this trend to continue with the greater numbers arriving to the Mediterranean climate zone.

Chapter 4

Alien plants in southern South America. A framework for evaluation and management of mutual risk of invasion between Chile and Argentina

Nicol Fuentes, Eduardo Ugarte, Ingolf Kühn & Stefan Klotz
under review in: *Biological Invasions*

Abstract

Most of the Chilean terrestrial exchange takes place across the frontier with Argentina. Road connections between both countries make possible the transport of alien plant species, incrementing the chance of new introductions and propagule pressure. We used a modified version of the Australian Weed Risk Assessment (WRA) method, to analyze if alien plant species already present either in Chile or Argentina can be a potential source of risk of alien introduction for the other country. We were interested to know quantitatively which country can be a source of a higher risk for its counterpart. We recorded 875 alien species; 288 exclusive to Chile, 283 exclusive to Argentina, and 304 shared by both countries. In terms of the risk of new alien introductions, Chile represents a higher threat to Argentina than vice versa. Twenty-two alien species exclusive to Chile, and present on road margins connecting both countries, are at the top risk level for Argentina; exclusive top risk alien species are absent from Argentinean road margins. Both countries have a similar number of exclusive alien species, but not present along road margins (Chile 162; Argentina 186), which can be a potential harmful to be introduced to the other country. The methodological approach proposed here may be a useful tool not only for screening potential alien plants introduction, but also in the prioritization of eradication or control measures of those species already introduced.

Introduction

Alien plant species can seriously damage agriculture and biodiversity conservation (Kowarik 2003, Pimentel *et al*. 2005, Thuiller *et al*. 2006). Prevention systems can be set-up starting from the species involved, via interaction between invasiveness (species), invasibility (recipient areas), and human disturbance (Rejmánek 2005, Rejmánek *et al*. 2005). Predicting which species will invade a new area, a basic task for scientists (Kolar & Lodge 2001), is difficult (Williamson 1999, Hulme 2003). Frequently, the lack of a consistent set of characteristics among invaders (Crawley 1987, Noble 1989), or interactions of complex nature (Küster *et al*. 2008), are in the way of any successful prediction (Williamson 1999, see also Pyšek & Richardson 2007).

Warning systems are designed to avoid the entry of new species, or restrain the spread of those already present (Zamora *et al*. 1989, Westbrooks 1991). Recent integrative approaches to invasion risk assessment are based on ratings of traits, invasiveness, and vulnerability, together with social and economic consequences (Hulme 2006, Vilà *et al*. 2006). As a pragmatic tool, plant invasion risk analysis combines the likelihood of introduction with its impacts on human society, agriculture, or health (Lonsdale 1999, Hulme *et al*. 2008). The screening methods have been successfully applied in Australia and New Zealand (Pheloung *et al*. 1999), South Africa (Tucker & Richardson 1995), Hawaii and Pacific Islands (Daehler & Carino 2000), Canada (Daehler & Denslow 2007), and USA (Reichard & Hamilton 1997).

The Australian Weed Risk Assessment (Pheloung *et al*. 1999, here after WRA) is based on 49 questions in three categories: biogeography, biology/ecology and undesirable traits. Each species obtains a final score, and is assigned to one of three options: *accepted*, *rejected* or *further evaluation* (see Methods). The WRA form can be adapted to different geographical locations (Gordon *et al*. 2008), incorporating economic consequences as well. It can aim at rating (and judging) plant species proposed for deliberate introduction. Although the WRA was designed to prevent the entry of noxious plants, WRA scores can also be used to evaluate alien species that are already present in the area of study (Daehler *et al*. 2004). In addition, WRA scores combined with alien's abundance (i.e. density, frequency, or biomass) provide relevant information to support eradication or control efforts (Daehler 2005).

An attractive scenario for exploring new approaches is provided by Chile, a biogeographical island (Arroyo *et al*. 1999) at the southern tip of South America. Close to one-half of all native vascular plant species are endemic (Marticorena 1990, Cowling *et al*. 1996) and the Chilean territory is considered a global hotspot (Cowling *et al*. 1996). Chile shares a long latitudinal border with Argentina, which is also considered a biogeographical island, although more open to the north. Consequently, Argentina has been connected with the more tropical part of South America (i.e. Paraguay, Bolivia, and Brazil). Both countries have a common history of colonization, and similar economic development traceable to the past five centuries (Ugarte *et al*. in press). Because most of the Chilean commercial exchange takes places across the frontier with Argentina, alien floras in each country can be assumed to be a potential mutual source of propagules. Road margins are probably the most relevant pathway for alien plant exchange between Chile and Argentina. It therefore seems reasonable to assume that particular species, inhabiting road margins, have a relatively better chance of arriving in the other country, either as a new introduction (eventually new invader), or as increased source of propagule pressure if the species is already present in both countries.

Here we used WRA method (Pheloung *et al*. 1999) to asses whether it is Chile or Argentina that poses the greatest risk in terms of the introduction of alien plants to the other country. Additionally, we ask whether or not alien species scores could be used as a sound basis for prioritising eradication or control measures. We propose a scheme for differentiating levels of the mutual risk of invasions between Chile and Argentina. We based our methodological approach on the following facts and assumptions. (*i*) From the addition of alien species present in both countries, a fraction is shared by both countries, while others are only present either in Chile or in Argentina exclusively (Fig. 1). (*ii*) Exclusive alien species were assigned highest risk to the chance of new introduction (new introduction risk), and then to the risk of incrementing propagule pressure via recurrent dispersal of those species already introduced (propagule pressure risk). (*iii*) Roads are the main pathway for commercial exchange between Chile and Argentina. Transportation by roads has increased 31% (from 2 million tons to 6.3 million tons) during the last 10 years (National Customs Service www.aduana.cl). (*iv*) Road interconnections take place across the Andes Mountain, which acts as a biogeographical barrier. (*v*) The long latitudinal border between both countries facilitates the transport of propagules, which can reach different biogeographical regions on both sides of the Andes Mountain.

Methods

Data source

A data base was prepared for alien species present in Chile and Argentina. Species were classified according to whether they were exclusive to one country (present in only one country) or shared (present in Chile and Argentina). Data for Chile was obtained from CONC Herbarium (Universidad de Concepción, Chile) and Matthei (1995). Data for Argentina was acquired from Zuloaga & Morrone (1996, 1999).

Because Herbarium data (Chile) and checklists (Argentina) exclude roadside locations of alien plants; data for roadsides were obtained by survey of four roads connecting the two countries. To analyze the main pathway of interchange (road margins) between both countries, we sampled four mains roads (Pehuenche, Pichachén, Pino Hachado, and Samoré) connecting Chile and Argentina across the Andes Mountain. These roads were selected to broadly cover the transition between the Mediterranean climate zone and temperate rain forest in Chile. In each country we sampled road sections of up to 30 km starting from the frontier of both countries (Lira *et al.* unpublished data) until the intersection with the first perpendicular main road. Each plot was 4m*20m every 5 to 6 km.

Applying the Weed Risk Assessment

We used a modified version of the Australian Weed Risk Assessment method to evaluate alien plant in Chile and Argentina (hereafter WRA-ChAr). The basic form comprises 49 questions in three sections: biogeography, biology/ecology, and undesirable traits. A minimum of 10 answers is required for a species to be evaluated: 2 answers in the biogeography section, 2 in undesirable traits, and 6 in biology/ecology section. The total score results in three possible options for each alien plant: *accepted* for introduction into the country (less than 1), *reject* for introduction into the country (over

6) or recommend for *further evaluation* (between 1 and 6). We modified questions 2.01, 2.04, 4.10, and 8.05 to represent Chilean and Argentinean features properly. In WRA, question 2.01 "Suitability of species to Australian climate" was changed to "Suitability to Chile or Argentinean climate". We made similar modification to question 2.04, "Native or naturalized in regions with extended dry periods" to "Native or naturalized in regions with climatic gradient, from desert to Patagonian steppe". The questions 4.10 "Grow on infertile soils" was modified to "Soils with thin organic layer and/or with high level of erosion (to Chile), and soils with thick organic layer or with medium level of erosion (to Argentina)". Finally, the question 8.05 "Effective natural enemies in Australia" was changed to "Effective natural enemies in Chile or Argentina". In the original WRA, answers to questions 2.01 and 2.02 (climate matching) are used to answer questions 3.01 to 3.05 related with "weed elsewhere". The system requires assigning maximum values (ten points in total; the default climate matching responses) if detailed climate matching for species is not available, as is the case for alien species in Chile and Argentina. Using default values resulted in all alien species *rejected*, even those of agricultural value (data not shown). Hence, we subtracted the points assign to climate matching for each species (ten points), and used the resulting scores for this study. To avoid tautology in screening procedure (Daehler & Carino 2000) we did not take into account species performance in Chile or Argentina when completing WRA-ChAr forms.

Information sources

Information for each species was obtained from Holm *et al*. (1977, 1979) and Weber (2003). Also we performed internet searches on the following data bases: A global compendium of weeds (http://www.hear.org); BiolFlor database on traits of vascular plants in Germany (http://www.biolflor.de) (Kühn *et al*. 2004); Department of Agriculture Natural Resources and Conservation Service, United States (http://plants.usda.gov); Department of the Environment and Water Resources, Australian Government (http://www.weeds.gov.au); Global Invasive Species Data Base (http://www.issg.org/database); Pacific Island Ecosystem at Risk (http://www.hear.org/pier); The Jepson herbarium (Jepson online interchange) (http://ucjeps.berkeley.edu/interchange) and Weed Risk Assessment for Hawaii and Pacific Island (http://www.botany.hawaii.edu).

Risk level assignments: first level according to presence/absence in countries and road margins

1. Collating taxonomic information and setting up a joint species list and constructing a data base (Fig. 1).
2. Sorting of alien species into: "exclusive to Chile", "exclusive to Argentina", and "shared" (in both Chile and Argentina) (Fig. 1).
3. Application of the WRA-ChAr method to each alien species. Sorting of *accepted*, *rejected* and *further evaluation*. Only *rejected* species were included in following steps (Fig. 1).
4. Within the group of exclusive alien species, we assigned a first risk level (5 very high) to those species present on roads margins (Fig. 1). Within the group of exclusives, a second level of risk (4 high) was assigned to those species not present on roads margins (Fig. 1). A third level of risk (3 medium) was attributed to those species shared by both countries and present in both road margins. A fourth level of risk (2 low) was assigned to those species present in both countries, but in Chilean roads only, or in Argentinean roads only. Finally, the fifth level of risk (1 very low) was assigned to the alien species shared by both countries but not present in road margins (Fig. 1).

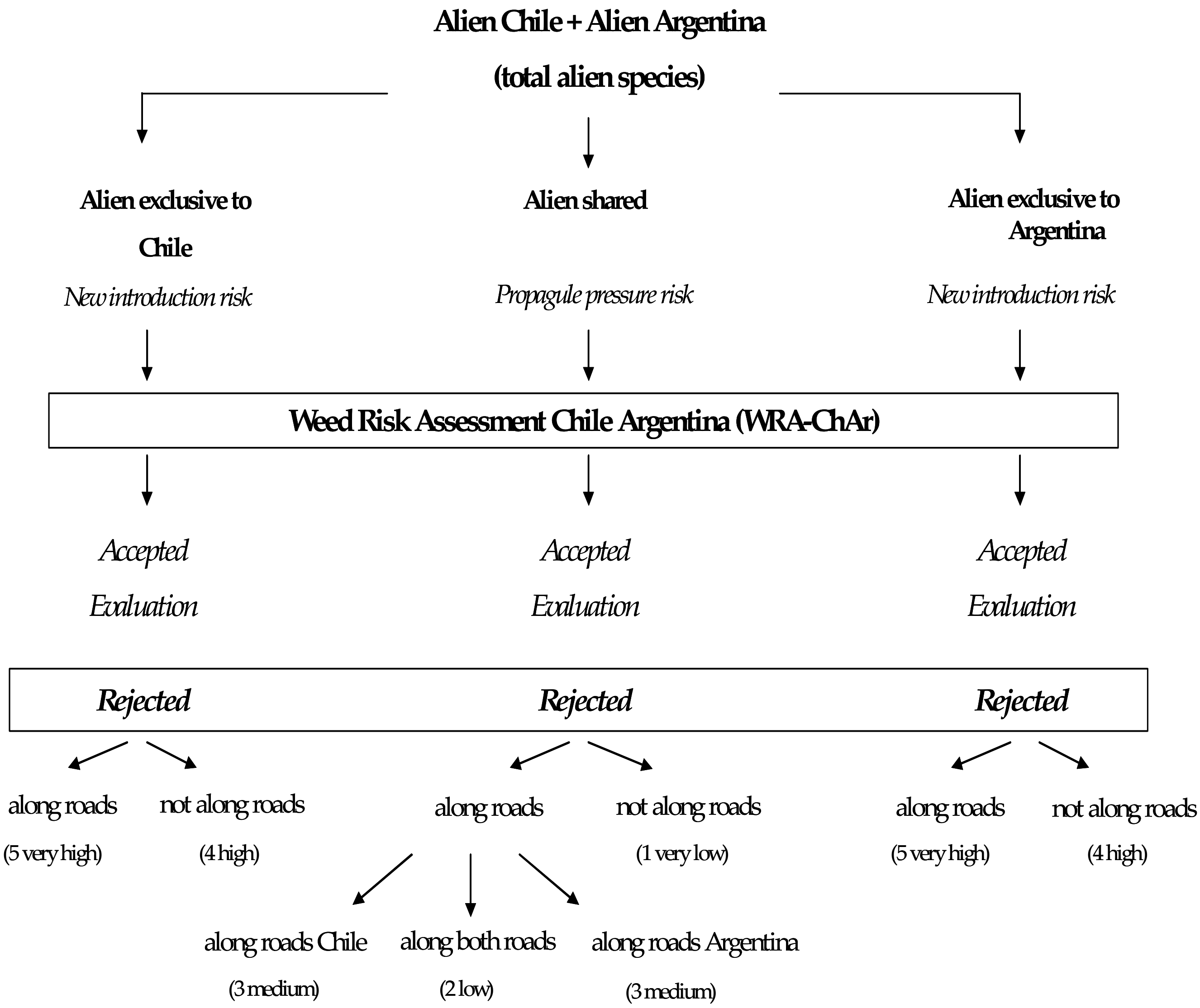

Figure 1 Risk assignment scheme of alien plant in Chile and Argentina based on presence/absence on countries and roads margins.

Second level: incorporating alien abundance in the country source

In order to develop an objective method of establishing priorities for alien species management or control, we developed an index "expansion on the territory index" (hereafter ET-index). Since we did not find any non linear relationship, we are allowed to divide the number of provinces where each alien species occurs, by its number of years of residence in the country. The ET-index is conceived as a proxy for alien abundance or alien's success, as it reflects expansion capacity in time on the study area.

Number of years of residence corresponds to the numbers of years since first report of the species in the territory (Fuentes *et al*. 2008). For those species for which information was available (species from CONC herbarium only) a second index was prepared incorporating the number of specimens of each species as an estimate of abundance on the territory. We calculated density per province (number of specimens of each species divided by province area) for all provinces where each species occur. The index was calculated dividing that total by the number of years of residence of the same species.

Results

In total we recorded 875 alien species; 288 exclusive to Chile, 283 exclusive to Argentina and 304 shared by both countries (Table 1, Appendix I).

Applying WRA-ChAr

The number of *accepted* alien species, in decreasing order, was highest for Argentina, followed by Chile, and then shared (Table 1). The number of those alien requiring *further evaluation* was nearly the same for Chile and Argentina, while the lowest number was for shared (Table 1). Likewise, the number of *rejected* species was practically the same for both countries. In contrast, the number of *rejected* for shared was the highest (Table 1). We did not find statistically significant differences among alien species *accepted*, *further evaluation*, and *rejected* (Fisher's exact test P = 0.12). In general, from the total species *rejected*, agriculture is the area with higher potential for being affected than environmental area in both countries (Table 1).

Table 1 Number of alien species exclusive to Chile, exclusive to Argentina, and shared. Number of alien species on *accepted, further evaluation,* and *rejected* category after WRA-ChAr. Proportions of the species (between brackets) regarding to the total number. Number of alien species with potential to invade agricultural areas, environmental areas, and both areas. Fisher's exact test among values of *accepted, further evaluation,* and *rejected*: $P = 0.12$.

	Exclusive to Chile	**Exclusive to Argentina**	**Shared**	**Total**
	288 (32.9%)	283 (32.3%)	304 (34.7%)	875
WRA-ChAr				
Accepted	1 (11.1%)	6 (66.7%)	2 (22.2%)	9
Evaluation	103 (37.3%)	91 (33%)	82 (29.7%)	276
Rejected	184 (31.2%)	186 (31.5%)	220 (37.3%)	590
Area affected (only *rejected* species)				
Agricultural	104 (30.9%)	98 (29.1%)	135 (40.1%)	337
Environmental	61 (30.3%)	71 (35.3%)	69 (34.3%)	201
Both areas	19 (36.5%)	17 (32.7%)	16 (30.8%)	52

Risk level assignments: first level

In terms of new species introduction, Chile represents a higher risk for Argentina than vice versa (Table 2). Twenty-two alien species exclusive to Chile and present on road margins are in rank 5 (very high), while no species were recorded in Argentina in the same category (Table 2). However, proportions of alien species in rank 4 (high) are fairly similar for both countries (Table 2). Twenty-two alien species were recorded in rank 3 (medium). No alien species resulted in rank 2 (low), whereas 198 alien species were assigned to rank 1 (low), potentially increasing propagule pressure in both countries (Table 2).

Table 2 Categories (sources of risk) and ranking according to the presence/absence of alien species on roads margins. Type of risk (new introduction or propagule pressure), and number of alien species on each category.

Category	rank	risk to Chile	risk to Argentina	type of risk	N° of species
Exclusive to Chile-along roads	5 (very high)		+	new introduction	22
Exclusive to Argentina-along roads	5 (very high)	+		new introduction	0
Exclusive to Chile-not along roads	4 (high)		+	new introduction	162
Exclusive to Argentina-not along roads	4 (high)	+		new introduction	186
in both countries-along roads in Chile and Argentina	3 (medium)	+	+	propagule pressure	22
in both countries-along Chilean roads only	2 (low)		+	propagule pressure	0
in both countries-along Argentina roads only	2 (low)	+		propagule pressure	0
in both countries-not along roads	1 (very low)	+	+	propagule pressure	198

Risk level assignments: second level

In Chile, we found a marginally significant but weak correlation between the ET-index and WRA-ChAr scores of *rejected* species, (Fig. 2a). Results for Argentina show no correlation between the ET-index and WRA-ChAr scores (Fig. 2b). While for the group of shared species the ET-index were positively though weakly correlated with WRA-ChAr scores in both countries (Fig. 2c, 2d).

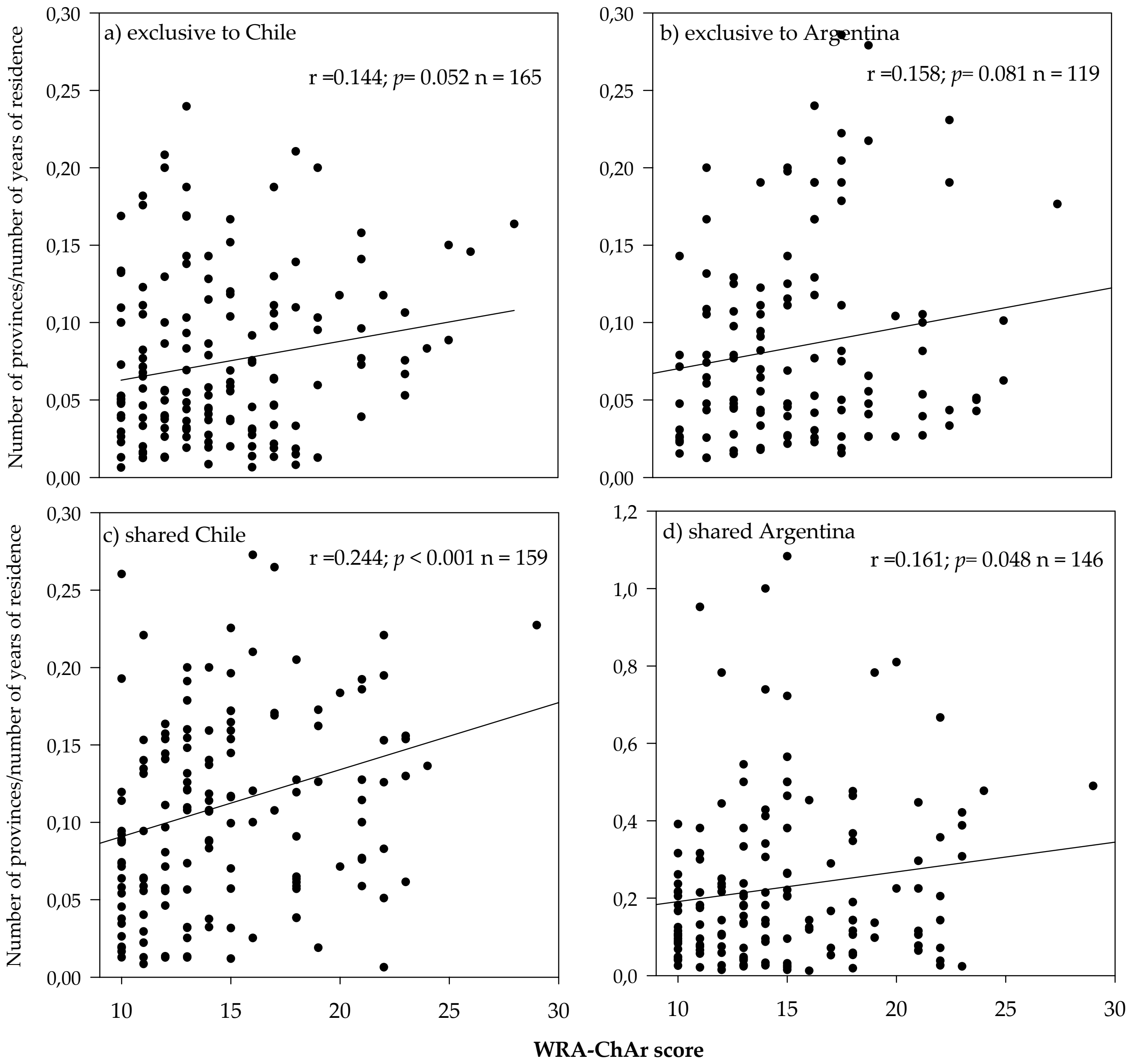

Figure 2 Correlation results between expansion on the territory index (ET-index; number of provinces divided by number of years of residence for each species) and WRA-ChAr score. *P* values and number of data for each correlation are given inside the figure.

Results of risk on the second level are showed on table 3 and Appendix I. Within the five categories, we sorted the species using our ET-index (Table 3). We present here only 22 exclusive alien species to Chile for discussion reasons, all species sorted by category and ET-index were listed in Appendix I.

Discussion

In southern South America, risk assessment systems for the introduction of new alien plant species does not yet exist, although an ongoing discussion in the scientific community and governmental agencies emphasizes the necessity of such protocols (Pauchard *et al*. 2004). The framework developed in this study gives an objective trait-based evaluation of the risk of new plant introductions in the context of the mutual invasion risk between countries that share a long border and a several roads connecting them. Here we discuss how to approach and deal with the particular interaction between Chile and Argentina.

From the evaluation of alien floras of Chile and Argentina (Table 1) three remarkable coincidences emerge. First, both territories have nearly the same total number of alien species (Chile 592; Argentina 587). Second, close to 50 % of the alien flora is shared by both countries, and third, WRA-ChAr analysis delivered a fairly similar number of *rejected* species in both countries (Chile 184; Argentina 186). The question remains open as to whether such outstanding coincidences are the consequence of comparable economical development culminating in equilibrium between both alien floras (Ugarte *et al*. in press), or whether they are the result of the invasiveness of alien species.

Scoring at first risk level

WRA-ChAr analysis rendered a substantial number of species in *further evaluation* and *rejected* categories. However, species in the *further evaluation* category can be re-examined through specially designed screening procedures (e.g. Daheler *et al*. 2004, Krivánek & Pyšek 2006).

Due to the fact that roads are the most relevant pathway for exchange between Chile and Argentina, the highest risk level was assigned to alien species present exclusively in one country and at the same time on road margins. At the other extreme, the lowest risk category grouped those shared by both countries and never found on road margins. Consequently, we are giving more weight to the introduction of a new species, than to the reinforcement of invasion of those already introduced, through propagule pressure via road margins.

Our assessments show that Chile represents a higher risk of alien introduction to Argentina than vice versa. We found twenty-two alien species present in Chilean road margins and absent in Argentina at the top risk level (rank 5 in our scale). However, an equivalent condition is absent in the opposite direction. The absence of alien plants in risk level 5 in Argentina can be explained by the following facts: (*i*) The altitudinal gradient (i.e. from the ocean to the Andes Mountain) in Chile is shorter compared with Argentina. Thus, alien species in Chile could spread faster along the altitudinal range than the alien species in Argentina. (*ii*) Observations show that on the Argentinean side, overgrazing on road margins (which is heavier than in Chile) can be effective in stopping new species introduction (Lira *et al*. unpublished data). (*iii*) The effect of the Andes Mountain, interacting with the rain-shadow effect that determines higher levels of rain in Chile than in Argentina (Veblen *et al*. 1983). Thus, at similar latitude there are different biogeographic regions both sides of the Andes (Arroyo *et al*. 1997) and species moving along the road will end up in a different biogeographical region than that of its source area. Overall, the twenty-two alien species should be placed under close supervision by Argentinean authorities, and Chile still has to take into account 150 species present in Argentina exclusively (rank 4), which could eventually move into road margins, increasing the threat of new introduction for Chile.

Scoring at second risk level - Risk balance and prioritization

The five groups resulting from first risk level categories can be ranked subsequently within each group to show their performance on real landscapes. We used the number of provinces combined with the number of years of residence (ET-index; see Methods) as a proxy for potential of spreading, and as measure of alien species' success.

Our results indicate a positive though weak correlation between ET-index and WRA-ChAr scores. However, the strength of the correlation increases when numbers of specimens are included as a measure of abundance ($r=0.16$; $P < 0.013$; species from Chile only). We are accepting *a priori* that those species faster in spreading over provinces will perform similarly in the new country and are consequently a higher source of risk. Increasing evidence indicates that the invasion process, in addition to a sensible rate of spreading, has to be reinforced by local abundance. The second risk level obtained can be used as guidance for decision-making in planning of eradication or control.

Following the ET-index, species with the highest priority will be those having a combination of a high number of provinces and low number of years of residence. These species are likely to pose a significant threat to the natural ecosystem, and they must be controlled. However, this species require high amount of resources to be eradicate or controlled. On the other hand, a species with low number of provinces but with a high number of years of residence will have a lower priority. When the priority of the species are similar in magnitude, it is possible to examine each species more closely to identify others factors that might help in making prioritization decisions, such as availability of cost-effective control methods and the availability of native species to replace an alien (Daehler 2005). The flexibility of the procedure and the possibility of reinterpreting and reassigning risk levels within the groups will be illustrated by the following cases.

Within the 22 species that represent very high risk values for Argentina, ET-index yields the highest value for *Parentucellia viscosa*, which in 48 years has reached 10 provinces in Chile. In contrast, *Anthemis arvensis* has covered only two provinces in 103 years. Within the 22 species, we can decide to give higher risk values to those causing more severe impacts (for instance loss of agricultural soil). We can conclude that woody species should be at the first risk level: in our case, *Rubus ulmifolius, Acacia dealbata, Rubus constrictus, Rosa rubiginosa, Cytisus striatus,* and *Robinia pseudoacacia,* are the candidates. If authorities require that the selection be narrowed down for a better allocation of resources following Daehler criteria's (2005), they will not pursue eradication of *R. ulmifolius, R. rubiginosa* or *A. dealbata*, which are widespread, as it would demand a high amount of resources, while its eradication would have minimal global effect. In contrast, if they concentrate resources on *C. striatus,* which is in its primary spreading phase, they will increase the chances of eradication, thereby avoiding the establishment of a new widespread pest in the long term.

This is the first overview of invasion risks between Chile and Argentina. Additionally, the protocol developed in this study must be empirically applied, and its practicability evaluated both by scientists and practical experts involved in the management of invasive plants. We suggest that common planning and control through cooperation among neighbour countries should be the more efficient way of investing public funds in prevention and control of plant invasions.

Table 3 Alien species *rejected* exclusive to Chile - along roads sorted by expansion on the territory index (ET-index; number of provinces divided by number of years of residence for each species). All species were classified into rank 5 (very high), based on the risk level assignments according to presence/absence in countries and road margins. NYR = number of years of residence, NP = number of provinces, A = agricultural areas, E = environmental areas, and B = both areas.

Exclusive to Chile - along roads	ET-index	WRA-ChAr	NYR	NP	area affected
Parentucellia viscosa	0.21	12	48	10	A
Verbascum virgatum	0.19	17	112	21	B
Rubus ulmifolius	0.16	28	110	18	A
Veronica serpyllifolia	0.15	15	112	17	A
Carduus nutans	0.11	23	47	5	E
Cynosurus echinatus	0.10	13	126	13	A
Verbascum thapsus	0.10	19	126	13	B
Phalaris canariensis	0.10	17	82	8	A
Acacia dealbata	0.10	19	126	12	E
Spergularia rubra	0.09	13	161	15	A
Rubus constrictus	0.09	25	79	7	B
Phalaris aquatica	0.09	14	81	7	E
Rosa rubiginosa	0.08	24	132	11	E
Boerhavia diffusa	0.07	15	116	8	A
Cytisus striatus	0.06	17	110	7	E
Tolpis barbata	0.06	12	126	7	A
Geranium robertianum	0.05	12	161	8	A
Juncus bufonius	0.04	12	153	6	A
Robinia pseudoacacia	0.04	15	110	4	E
Lotus uliginosus	0.03	16	160	5	B
Petrorhagia prolifera	0.03	13	65	2	E
Anthemis arvensis	0.02	14	103	2	A

Chapter 5

Synthesis

1. Summary of the objectives

The central aims of this investigation were: (*i*) To improve the knowledge about the invasion history and the drivers of alien species abundance in Chile. (*ii*) To quantify the importance of human disturbance, socioeconomic activities, and climatic gradients. (*iii*) To evaluate the current and future risks of alien plant species invasion in Chile. Therefore I firstly analyzed the pattern of accumulation of herbarium specimens in order to trace back the distribution in time of alien plant species introductions into the Chilean territory. Secondly, I examined the relationship between alien plant density and two groups of proxies for accounting for the degree of disturbance related to socio-economic and land-use variables. Thirdly, I used a modified version of the Australian Weed Risk Assessment (WRA) method to evaluate the current and future risks of alien plants invasion in Chile and additionally, I propose priorities for their management.

2. Summarizing discussion

The number of alien plants inhabiting the Chilean territory will continue increasing taking into account that the curve of species accumulation is not yet asymptotic (chapter 2). Hence, it can be possible to predict that further geographical sources of alien plants (underrepresented up to now) will become more significant, considering the new trade agreements already established by Chile (e.g. the Mercosur trade agreement with Argentina and Brazil; and the Asia-Pacific trade agreement with Asian countries, Australia, and New Zealand). Insofar as new invasions are concerned, many alien plants found in climatically similar areas are potential candidates. For instance, the Mediterranean region of Chile has not yet acquired the alien species density seen in other Mediterranean regions of the world (i.e. California, Pauchard *et al*. 2004). Additionally, it would be necessary to pay more attention to alien plants occurring in neighboring countries in the southern hemisphere in order to avoid mutual invasions.

In almost five centuries alien species have expanded to nearly all the territory (chapter 2). It is surprising that some alien species introduced into Chile less than 500 years ago are adapted to the wide range of environmental conditions along the latitudinal gradient that the country represents (44° of latitude). However, both the North and South extremes of the territory seem to be an exception to this general trend, probably because the harsh climatic conditions prevailing in both extremes (desert and cold steppe) are important filters limiting the distribution of alien plants in those zones. I found that both in the North and South extremes alien species density is mainly correlated with agricultural activities (chapter 3). Certainly, this activity offers the chances of bringing in alien plant propagules as seed contaminants, and it gives to the alien plants the opportunity to establish in disturbed arable landscapes as well as in irrigated areas under cultivation. These facts suggest that further increases in the amount of agricultural sector will result in an increase of the number of alien plants species in those areas. Nevertheless, as the agricultural activities can not be minimized, in those areas a proper monitoring system will be necessary to avoid or reduce new alien plant introductions.

Most of the alien plants species present in Chile concentrate in the Mediterranean and temperate rainy regions (chapter 2 and 3). A possible explanation to this pattern can be the fact that aliens have arrived to Chile for more than four centuries, with significant arrivals beginning with Spanish colonization to these regions (chapter 2). Furthermore, the biogeographic characteristics of the Mediterranean and temperate regions of the Chilean territory favored the introduction and spreading of alien plant species (Torrejón & Cisternas 2002). Currently, the high density of alien plant species in the Mediterranean and temperate rainy regions represent a high risk in terms of biodiversity conservation efforts, as this territory has been catalogued as a hotspot of world biodiversity (Cowling *et al*. 1996), and new alien plants are estimated to arrive as a result of trade and tourism (Arroyo *et al*. 2000).

From the beginning of the introduction to Chile, alien plant species have been related to human disturbances and economic activities (chapter 2). Road density and agricultural activities resulted to be the major driving forces of alien plant distributions in the country to day. At a practical level, much more attention needs to be given to preventive measures dealing with new alien plant introductions. If those activities are the main drivers of the alien species spread (chapter 3), they should be monitored permanently to avoid new alien plant introductions, and the spread of those species being more invasive.

In Chile, a risk assessment system for the introduction of new alien plant species does not yet exist, although an ongoing discussion in the scientific community and governmental agencies emphasizes the necessity of such protocols. The framework developed in this thesis (chapter 4) gives an objective evaluation of the risk of new plant introductions in the context of the mutual invasion risk between countries that share a long border and a several roads connecting them, namely Chile and Argentina. In terms of the risk of new introductions, the Chilean territory represents a higher threat to Argentina than vice versa. However, both countries showed an almost similar number of alien plants species currently only found on their respective territory, which can be a potential threat to be introduced to the other country. The results obtained in this thesis may help to develop a guideline for a sustainable land management directed at avoiding the expansion of alien invaders by targeting dispersal pathways, and limiting anthropogenic disturbances associated with increasing risk of alien plant invasions.

Because land managers rarely dispose of sufficient resources to eradicate or control all invasive plants, inevitably priories must be established. I build up a simple rating system to set up priorities for eradication or control of alien plant species in Chile (chapter 4). As the mentioned system is simple and spread-sheet based it can be used by land managers and conservation agencies. Clearly, such a system must be applied and its practicability evaluated both by scientists and practical experts involved in the management of invasive plants species. Overall, the next step should be the application of a priority rating system of a set of alien species with highest priority ratings for eradication or control, and to investigate the response of those alien plants in the long term.

3. Conclusions

Assessments of the patterns and processes of alien plants invasion in time and space are essential components of our understanding of these enormously important biological phenomena (Mooney & Cleland 2001, Sala *et al*. 2000). Alien plant species seem to invade more often habitats altered by humans, such as agricultural fields and roads margins. Hence, documenting the past spread, the current distribution, and the potential future risk of new introductions and dispersal are important components of ecosystem monitoring.

Many of the projections of this thesis are based on data that could be considered "imperfect" (herbarium records). Nonetheless, I think that the approaches followed here establish a rational framework for more comprehensive assessment in the future. Being aware of the limitations associated with herbarium data, these should not undermine the potential of this information source to assist in the study of alien plants threat. However, herbarium data should not be relied upon as the sole data source, but a taxonomic framework must be established, and a database compiled and supplemented with extensive fieldwork. Given the increasing demand for baseline information by land managers and the cost of collecting such data in complementary ways, herbarium data should be utilized as completely as possible.

The results of this thesis suggest increases in the number of alien plant species in Chile. Under this situation, national responsibilities for prevention, early detection, and control of alien plant species must be defined. Improvement of the framework developed here to the point that they are useful to policy-makers will require quantitative regional analyses and the study of the interactions among economic and ecological impacts. Economic and ecological models should be used as part of the assessment and management process to estimate the potential consequences of the establishment of a specific alien plant species. Assessments of economic impacts will be highly desirable, because the public decision-makers and legislators understand monetary impacts, costs, and benefits while they may not understand the implications of the impacts presented solely in ecological terms.

Additional research should be aiming at identifying habitats or ecosystems under high priority for management or control of the alien plant species invasion. The assessment of alien plant species effects on ecological patterns and processes of native species, ecosystem properties (e.g. primary productivity, soil water content, etc.), and on the economy represents one of the major challenges for the scientific community and society in Chile. The comprehensive national database of alien plant species developed here (including their distributions, past spread, potential future dispersal, and the threat they pose) can be used as the starting point of the mentioned challenges. Finally, this database should be disseminated to generate public understanding of the plant invasion phenomenon, and also be integrating into international databases to contribute to an accessible global knowledge base of alien plant species problem.

General Bibliography

Armesto, J.J., Rozzi, R., Smith-Ramírez, C. & Arroyo, M.K.T. (1998) Conservation targets in South American temperate forests. *Science*, 279: 1271-1272.

Aronson, J., Del Pozo, A., Ovalle, C., Avendaño, J., Lavin, A. & Etienne, M. (1998) Land use changes and conflicts in Central Chile. In: *Landscape Disturbance and Biodiversity in Mediterranean-Type Ecosystems*, (ed. by Rundel, P.W., Montenegro, G. & Jaksic, F.), pp. 155-168. Springer-Verlag, Berlin, Germany.

Arroyo, M.T.K., Cavieres, L., Marticorena, C. & Muñoz-Schick, M. (1995) Convergence in the Mediterranean floras in central Chile and California: insights from comparative biogeography. In: *Ecology and Biogeography of Mediterranean Ecosystems in Chile, California, and Australia*, (ed. by Arroyo, M.T.K., Zedler, P.H. & Fox, M.D.), pp. 43-88. Springer-Verlag, New York.

Arroyo, M.T.K., Marticorena, C., Matthei, O. & Cavieres, L. (2000) Plant invasions in Chile: Present patterns and future predictions. In: *Invasive Species in a Changing World*, (ed. by Mooney, H.A. & Hobbs, R.J.), pp. 385-421. Island Press, USA.

Arroyo, M.T.K., Riveros, M., Peñaloza, A., Cavieres, L. & Faggi, A.M. (1996) Phytogeographic relationships and regional richness patterns of the cool temperate rainforest flora of southern South America. In: *High - Latitude Rainforests and Associated Ecosystems of the West Coasts of the Americas. Climate, Hydrology, Ecology and Conservation*, (ed. by Lawford, R.G., Alaback, P.B. & Fuentes, E.), pp. 134-172. Springer-Verlag, New York.

Arroyo, M.T.K., Cavieres, L., Peñaloza, A., Riveros, M. & Faggi, A.M. (1997) Phytogeographic relationships and species richness patterns in the temperate rain forest flora of South America. In: *Ecología de los bosques nativos de Chile*, (ed. by Armesto, J.J., Villagrán, C. & Arroyo, M.T.K.), pp. 71-100. Editorial Universitaria, Santiago de Chile.

Arroyo, M.T.K., Rozzi, R., Simonetti, J.A., Marquet, P. & Sallaberry, M. (1999) Central Chile. In: *Hotspots: earth's biologically richest and most endangered terrestrial ecosystems*, (ed. by Mittermeier, R.A., Myers, N., Robles-Gil, P. & Goettsch- Mittermeier, C.), pp. 161-171. Cemex, Conservation Internacional, Ciudad de Mexico.

Aschmann, H. & Bahre, C. (1977) Man's impact on the wild landscape. In: *Convergent evolution in Chile and California Mediterranean Climate Ecosystems*, (ed. by Mooney, H.A.), pp. 73-84. Hutchinson and Ross Inc., Pennsylvania.

Axelrod, D.I., Arroyo, M.T.K. & Raven, P. (1991) Historical development of temperate vegetation in the Americas. *Revista Chilena De Historia Natural*, 64: 413-446.

Baker, H.G. (1965) Characteristics and modes of origin of weeds. In: *The Genetics of Colonizing Species*, (ed. by Baker, H.G. & Stebbins, G.L.), pp. 147-69. New York.

Baker, H.G. (1974) The evolution of weeds. *Annual Review of Ecology and Sistematics*, 5: 1-24.

Blossey, B. & Notzold, R. (1995) Evolution of increased competitive ability in invasive non-indigenous plants: a hypothesis. *Journal of Ecology*, 83: 887-89.

Blossey, B. Skinner, L.C. & Taylor, J (2001) Impact and management of purple loosestrife (*Lythrum salicaria*) in North America. *Biodiversity and Conservation*, 10: 1787-1807.

Burke, M.J.W. & Grime, J.P. (1996) An experimental study of plant community invasibility. *Ecology*, 77: 776-790.

Cariola, C. & Sunkel, O. (1982) *Un siglo de historia económica de Chile 1830 - 1930, dos ensayos y una bibliografía*. Ediciones cultura hispánica del Instituto de Cooperación Iberoamericana, España.

Castro, S.A., Figueroa, J.A., Muñoz-Schick, M. & Jaksic, F.M. (2005) Minimum residence time, biogeographic origin, and life cycle as determinants of the geographical extent of naturalized plants in continental Chile. *Diversity and Distributions*, 11: 183-191.

CBD (2007) The convention on biological diversity. <http://www.cbd.int/convention/convention.shtml>

Chapin III, F.S., Reynolds, H.L., D'Antonio, C.M. & Eckhart, V.M. (1996) The functional role of species in terrestrial ecosystems. In: *Global Change and Terrestrial Ecosystems*, (ed. by Walter, B. & Steffen, W.), pp. 403-428. Cambridge University Press, Cambridge

Cincotta, R.P., Wisnewski, J. & Engelman, R. (2000) Human population in the biodiversity hotspots. *Nature*, 404: 990-992.

Cook, R.D. (1977) Detection of Influential Observation in Linear Regression. *Technometrics*, 19: 15-18.

Cowling, R.M., Rundel, P.W., Lamont, B.B., Arroyo, M. & Arianoutsou, M. (1996) Plant diversity in Mediterranean climate regions. *Trends in Ecology and Evolution*, 11: 362-366.

Crawley, M.J. (1987) What makes a community invasible?. In: *Colonization, Succession, and Stability*, (ed. by Gray, A.J., Crawley, M.J. & Edwards, P.J.), pp. 429-53. Blackwell Scientific, Oxford.

Crosby, A.W. (1972) *The Columbian Exchange*: *Biological and Cultural Consequences of 1492*. Contributions in American Studies, Westport Connecticut, Greenwood Publishing Co.

D'Antonio, C.M. & Mahall, B.E. (1991) Root profiles and competition between the invasive, exotic perennial, *Carpobortus edulis,* and two native shrub species in California coastal scrub. *American Journal of Botany*, 78: 885-894.

D'Antonio, C.M. & Vitousek, P.M. (1992) Biological invasions by exotic grasses, the grass/fire cycle and global change. *Annual Review of Ecology and Systematics*, 23: 63-87.

Daehler, C. (2005) Invasive species. In: *Biodiversity Assessment of Tropical Island Ecosystems PABITRA manual for interactive ecology and management*, (ed. by Mueller-Dombois, D., Bridges, K.W. & Daehler, C.), pp. 197-208. Honolulu, Hawaii.

Daehler, C. & Carino, D.A. (2000) Predicting invasive plants: prospects for a general screening system based on current regional models. *Biological Invasions*, 2: 92-103.

Daehler, C. & Denslow, J.S. (2007) The Australian weed risk assessment system: Does it work in Hawaii? Would it work in Canada?. In: Invasive plants Inventories, strategies and action Topics in Canadian Weed Science, (ed. by Clements, R.D. & Darbyshire, S.J.), pp. 9-24. Canadian Weed Science Society, Quebec.

Daehler, C., Denslow, J.S., Ansari, S. & Kuo, H. (2004) A risk assessment system for screening out harmful invasive pest plants from Hawai'i and other Pacific Islands. *Conservation Biology*, 18: 360-368.

Dalmazzone, S. (2000) Economic factors affecting vulnerability to biological invasions. In: *The economics of biological invasions*, (ed. by Perrings, C., Williamson, M. & Dalmazzone, S.), pp. 17-30. Edward Elgar Publishing, Cheltenham.

Davis, M.A. & Thompson, K. (2000) Eight ways to be a colonizer; two ways to be an invader: a proposed nomenclature scheme for invasion ecology. *Bulletin of the Ecological Society of America*, 81: 226-30.

Delisle, F., Lavoie, C., Jean, M. & Lachance, D. (2003) Reconstructing the spread of invasive plants: taking into account biases associated with herbarium specimens. *Journal of Biogeography*, 30: 1033-1042.

di Castri, F. (1989) History of biological invasions with special emphasis on the Old World. In: *Biological invasions: a global perspective*, (ed. by Drake, J.R., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, F.J., Rejmánek, M. & Williamson, M), pp. 1-30. Scientific committee on problems of the environment (SCOPE). John Wiley and Son, New York.

di Castri, F. & Hajek, E. (1976) *Bioclimatología de Chile*. Vicerrectoría Académica, Pontificia Universidad Católica de Chile, Santiago.

di Castri, F., Hansen, A.J. & Debussche, M. (1990) *Biological Invasions in Europe and the Mediterranean Basin*. Kluwer Academic Publishers, Netherlands.

Donoso, C. & Lara, A. (1996) Utilización de los bosques nativos en Chile: pasado, presente y futuro. In: *Ecología de los bosques nativos de Chile*, (ed. by Armesto, J.J., Arroyo, M.T.K. & Villagrán, C.), pp. 234-255. Editorial Universitaria, Chile.

Elton, C.S. (1958) *The ecology of invasions by animals and plants.* Methuen, London.

Figueroa, J., Castro, S., Marquet, P. & Jaksic, F. (2004) Exotic plant invasion to the Mediterranean region of Chile: causes, history and impacts. *Revista Chilena de Historia Natural*, 77: 465-483.

Fuentes, N., Ugarte, E., Kühn, I. & Klotz, S. (2008) Alien plants in Chile: Inferring invasion periods from herbarium records. *Biological Invasions*, 10: 649-657.

Gaudet, C.L. & Keddy, P.A. (1988) Predicting competitive ability from plant traits: a comparative approach. *Nature*, 334: 242-243.

Gimaret-Carpentier, C., Dray, S. & Pascal, J.P. (2003) Broad–scale biodiversity pattern of the endemic tree flora of the Western Ghats (India) using canonical correlation analysis of herbarium records. *Ecography*, 26: 429-444.

Glowka, L., Burhenne-Guilmin, F. & Synge, H. (1994) *A guide to the convention on biological diversity*. IUCN, Gland.

Gordon, D., Onderdonk, D., Fox, A. & Stocker, R. (2008) Consistent accuracy of the Australian weed risk assessment system across varied geographies. *Diversity and Distribution*, 14: 234-242.

Hinojosa, L.F. & Villagrán, C. (1997) Historia de los bosques del sur de Sudamérica I: antecedentes paleobotánicos, geológicos y climáticos del Terciario del cono sur de América. *Revista Chilena de Historia Natural*, 70: 225-239.

Hodkinson, D.J. & Thompson, K. (1997) Plant dispersal: the role of man. *Journal of Applied Ecology*, 34: 1484-1496.

Holm, L., Pancho, J.V., Herberger, J.P. & Plucknett, D.L. (1979) *A Geographical Atlas of World Weeds*. Wiley-Interscience, New York.

Holm, L., Plucknett, D.L., Pancho, J.V. & Herberger, J.P. (1977) *The world's worst weeds*. University Press of Hawaii.

Hulme, P. (2003) Biological invasions: winning the science battles but losing the conservation war?. *Oryx*, 37: 178-193.

Hulme, P. (2006) Beyond control: wider implications for the management of biological invasions. *Journal of Applied Ecology*, 43: 835-847.

Hulme, P., Bacher, S., Kenis, M., Klotz, S., Kühn, I., Minchin, D., Nentwig, W., Olenin, S., Panov, V., Pergl, J., Pyšek, P., Roques, A., Sol, D., Solarz, W. & Vilà, M. (2008) Grasping at the routes of biological invasions: a framework for integrating pathways into policy. *Journal of Applied Ecology*, 45: 403-414.

Jaksic, F.M. (1998) Vertebrate invaders and their ecological impacts in Chile. *Biodiversity and Conservation*, 7: 1427-1445.

Jaksic, F.M. & Fuentes, E.R. (1991) Ecology of a successful invader: the European rabbit in central Chile. In: *Biogeography of Mediterranean Invasions*, (ed. by Groves, R.H. & di Castri, F.), pp. 273-283. Cambridge University Press, Cambridge.

Keller, R.P., Lodge, D.M. & Finnoff, D.C. (2007) Risk assessment for invasive species produces net bioeconomic benefits. *Proceedings of the National Academy of Sciences of the United States of America*, 104: 203-207.

Kolar, C.S. & Lodge, D.M. (2001) Progress in invasion biology: predicting invaders. *Trends in Ecology and Evolution*, 16: 199-204.

Kowarik, I. (2003) Human agency in biological invasions: secondary releases foster naturalization and population expansion of alien plant species. *Biological Invasions*, 5: 293-312.

Krivánek, M. & Pyšek, P. (2006) Predicting invasions by woody species in a temperate zone: a test of three risk assessment schemes in the Czech Republic (Central Europe). *Diversity and Distributions*, 12: 319-327.

Kühn, I., Durka, W. & Klotz, S. (2004) BiolFlor - a new plant-trait database as a tool for plant invasion ecology. *Diversity and Distributions*, 10: 363-365.

Küster, C., Kühn, I., Bruelheide, H. & Klotz, S. (2008) Trait interactions help explain plant invasion success in the German flora. *Journal of Ecology*, 96: 860-868.

Lambdon, P., Pyšek, P., Basnou, C., Arianoutsou, M., Ess, F., Hejda, M., Jarošík, V., Pergl, J., Winter, M., Anastasiu, P., Andriopoulos, P., Bazos, I., Brundu, G., Celesti-Grapow, L., Chassot, P., Delipetrou, P., Josefsson, M., Kark, S., Klotz, S., Kokkoris, Y., Kühn, I., Marchante, H., Perglová, I., Pino, J., Vilà, M., Zikos, A., Roy, D. & Hulme, P. (2008) Alien flora of Europe: species diversity, temporal trends, geographical patterns and research needs. *Preslia*, 80: 101-149.

Lavoie, C. & Dufresne, C. (2005) The spread of reed canarygrass (*Phalaris arundinacea*) in Québec: A spatio-temporal perspective. *Ecoscience*, 12: 366-375.

Lavoie, C., Jean, M., Delisle, F. & Létourneau, G. (2003) Exotic plant species of the St Lawrence River wetlands: a spatial and historical analysis. *Journal of Biogeography*, 30: 537-549.

Levine, J.M. (2000) Species diversity and biological invasions: relating local process to community pattern. *Science*, 288: 852-854.

Levine, J.M. & D'Antonio, C.M. (1999) Elton revisited: a review of evidence linking diversity and invasibility. *Oikos*, 87: 15-26.

Levine, J.M., Kennedy, T. & Naeem, S. (2002) Neighborhood scale effects of species diversity on biological invasions and their relationship to community patterns. In: *Biodiversity and Ecosystem Functioning*, (ed. by Loreau, M., Naeem, S. & Inchausti, P.), pp. 114-124. Oxford University Press, Oxford.

Lienert, J., Fischer, M. & Diemer, M. (2002) Local extinctions of the wetland specialist *Swertia perennis* L. (Gentianaceae) in Switzerland: a revisitation study based on herbarium records. *Biological Conservation*, 103: 65-76.

Liu, J., Liang, S., Liu, F., Wang, R. & Dong, M. (2005) Invasive alien plant species in China: regional distribution patterns. *Diversity and Distributions*, 11: 341-347.

Lockwood, J.L., Cassey, P. & Blackburn, T. (2005) The role of propagule pressure in explaining species invasions. *Trends in Ecology and Evolution*, 20: 223-228.

Loh, R.K. & Daehler, C. (2008) Influence of woody invader control methods and seed availability on native and invasive species establishment in a Hawaiian forest. *Biological Invasions*, 10: 805-819.

Lonsdale, W.M. (1999) Global patterns of plant invasions and the concept of invasibility. *Ecology*, 80: 1522-1536.

Lonsdale, W.M. & Braithwaite, R.W. (1988) The shrub that conquered the bush. *New Scientist*, 120: 52-55.

Lonsdale, W.M. & Lane, A.M. (1994) Tourist vehicles as vectors of weed seeds in Kakadu National Park, Northern Australia. *Biological Conservation*, 69: 277-283.

MacDougall, A.S., Loo, J.A., Clayden, S.R., Goltz, J.G. & Hinds, H.R. (1998) Defining conservation priorities for plant taxa in southeastern New Brunswick, Canada using herbarium records. *Biological Conservation*, 86: 325-338.

Mack, M.C. & D'Antonio, C.M. (1998) Impacts of biological invasions on disturbance regimes. *Trends in Ecology and Evolution*, 13: 195-198.

Mack, R.N. (2000) Cultivation fosters plant naturalization by reducing environmental stochasticity. *Biological Invasions*, 2: 111-122.

Mack, R.N., Simberloff, D., Lonsdale, W.M., Evans, H., Clout, M. & Bazzaz, F.A. (2000) Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecological Applications*, 10: 689-710.

Mandák, B., Pyšek, P. & Kateřina, B. (2004) History of the invasion and distribution of *Reynoutria* taxa in the Czech Republic: a hybrid spreading faster than its parents. *Preslia*, 76: 15-64.

Marticorena, C. (1990) Contribución a la estadística de la flora vascular de Chile. *Gayana Botanica*, 47: 85-113.

Marticorena, C. & Rodríguez, R. (1995) *Flora de Chile*, I: Pteridophyta-Gymnospermae. Universidad de Concepción, Concepción, Chile.

Marticorena, C. & Rodríguez, R. (2001) *Flora de Chile*, 2: Winteraceae-Ranunculaceae. Universidad de Concepción, Concepción, Chile.

Matthei, O. (1995) *Manual de las malezas que crecen en Chile*. Alfabeta Impresores, Chile.

Mellado, M.Z. (2007) *El trigo en Chile Cultura, Ciencia y Tecnología*. Ograma Impresiones, Chile.

Mihulka, S. & Pyšek, P. (2001) Invasion history of *Oenothera* congeners in Europe: a comparative study of spreading rates in the last 200 years. *Journal of Biogeography*, 28: 597-609.

Montenegro, G., Teillier, S., Arce, P. & Poblete, V. (1991) Introduction of plant into Mediterranean-type climate area of Chile. In: *Biogeography of Mediterranean Invasion*, (ed. by Gorbes, R.H. & di Castri, F.), pp. 103-114. Cambridge University Press, Cambridge.

Mooney, H. & Cleland, E. (2001) The evolutionary impact of invasive species. *Proceedings of the National Academy of Science of the United States of America*, 98: 5446-5451.

Mostny-Glaser, G. & Niemeyer-Fernández, H. (1983) Museo Nacional de Historia Natural. Dirección de Bibliotecas. Archivos y Museos. Ministerio de Educación Pública, Santiago de Chile.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G. & Kent, J. (2000) Biodiversity hotspots for conservation priorities. *Nature*, 403: 853-858.

Noble, I.R. (1989) Attributes of invaders and the invading process: terrestrial and vascular plants. In: *Biological invasions: a global perspective*, (ed. by Drake, J.A., Mooney, H.A., di Castri, F., Groves, R.H., Kruger, F.J., Rejmanek, M. & Williamson, M.H.), pp. 301-13. Wiley, Chichester.

Ormazabal, C. (1993) The conservation of biodiversity in Chile. *Revista Chilena de Historia Natural*, 66: 383-402.

Panetta, F. D. (1993). A system of assessing proponed plant introductions for weed potential. *Plant Protection Quarterly*, 8: 10-14.

Panetta, F.D. & Mitchell, N.D. (1991) Homoclime analysis and the prediction of weediness. *Weed Research*, 31: 273-284.

Parker, I.M., Simberloff, D., Lonsdale, W.M., Goodell, K., Wonham, M., Kareiva, P.M., Williamson, M.H., Von Holle, B., Moyle, P.B., Byers, J.E. & Goldwasser, L. (1999) Impact: toward a framework for understanding the ecological effects of invaders. *Biological Invasions*, 1: 3-19.

Pauchard, A. & Alaback, P. (2004) Influence of elevation, land use, and landscape context on patterns of alien plant invasions along roadsides in protected areas of south-central Chile. *Conservation Biology*, 18: 238-248.

Pauchard, A., Alaback, P. & Edlund, E. (2003) Plant invasions in protected areas at multiple scales: *Linaria vulgaris* (Scrophulariaceae) in the West Yellowstone area. *Western North American Naturalist*, 63: 416-428.

Pauchard, A., Cavieres, L., Bustamante, R., Becerra, P. & Rapoport, E. (2004) Increasing the understanding of plant invasions in southern South America: First symposium on Alien Plant Invasions in Chile. *Biological Invasions*, 6: 255-257.

Peña, E., Hidalgo, M., Langdon, B. & Pauchard, A. (2008) Patterns of spread of *Pinus contorta* Dougl. ex Loud. invasion in a Natural Reserve in southern South America. *Forest Ecology and Management*, 256: 1049-1054.

Perrings, C., Dehnen-Schmutz, K., Touza1, J. & Williamson, M. (2005) How to manage biological invasions under globalization. *Trends in Ecology and Evolution*, 20: 212-215.

Perrings, C., Williamson, M., Barbier, E.B., Delfino, D., Dalmazzone, S., Shogren, J., Simmons, P. & Watkinson, A. (2002) Biological invasion risks and the public good: an economic perspective. *Conservation Ecology*, 6: 1-7.

Pheloung, P.C., Williams, P.A. & Halloy, S. R. (1999) A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *Journal of Environmental Management*, 57: 239-251.

Philippi, R.A. (1882) *Catálogo de plantas cultivadas para el Jardín Botánico de Santiago hasta el 1° de mayo de 1881.* Imprenta Nacional, Santiago de Chile.

Pimentel, D., Lach, L., Zuniga, R. & Morrison, D. (2000) Environmental and economic costs of nonindigeniuos species in the United States. *Bioscience*, 50: 53-63.

Pimentel, D., Zuniga, R. & Morrison, D. (2005) Update on the environmental and economic costs associated with alien-invasive species in the United States. *Ecological Enonomics*, 52: 273-288.

Pino, J., Font, X., Carbó, J., Jové, M. & Pallarès, L. (2005) Large-scale correlates of alien plant invasion in Catalonia (NE of Spain). *Biological Conservation*, 122: 339-350.

Pyšek, P. (1998) Is there a taxonomic pattern to plant invasions?. *Oikos*, 82: 282-294.

Pyšek, P. & Prach, K. (1993) Plant invasion and the role of riparian habitats: a comparison of four species alien to central Europe. *Journal of Biogeography*, 20: 413–420.

Pyšek, P. & Prach, K. (1995) Invasion dynamics of *Impatiens glandulifera*: a century of spreading reconstructed. *Biological Conservation*, 74: 41-48.

Pyšek, P. & Richardson, D.M. (2007) Traits associated with invasiveness in alien plants: Where do we stand?. In: *Biological invasions, Ecological Studies 193* (ed. by Nentwig, W.), pp. 97-126. Springer-Verlag Berlin, Heidelberg.

Pyšek, P., Müllerová, J. & Jarošík, V. (2007) Historical dynamics of *Heracleum mantegazzianum* invasion at regional and local scales. In: *Ecology and Management of Giant Hogweed* (*Heracleum mantegazzianum*), (ed. by Pyšek, P., Cock, M.J.W., Nentwig, W. & Ravn, H.P.), pp. 42-54. CAB International, Oxford.

Reichard, S.H. & Hamilton, C.W. (1997) Predicting invasions of woody plants introduced into North America. *Conservation Biology*, 11: 193-203.

Rejmánek, M. (2005) Invasive plants: what we know and what we want to know. *American Journal of Botany*, 92: 901-902.

Rejmánek, M. & Randall, J. (1994) Invasive alien plants in California: 1993 summary and comparison with other areas in North America. *Madroño* 41: 161-177.

Rejmánek, M., Richardson, D.M., Higgins, S.I., Pitcairn, M.J. & Grotkopp, E. (2005) Ecology of invasive plants: state of the art. In: *Invasive alien species: a new synthesis*, (ed. by Mooney, H.A., Mack, R.N., McNeely, J.A., Neville, L., Schei, P.J. & Waage, J.), pp. 104-61. Island Press, Washington.

Richardson, D.M., Pyšek, P., Rejmanek, M., Barbour, M.G., Panetta, F.D. & West, C.J. (2000) Naturalization and invasion of alien plants: concepts and definitions. *Diversity and Distributions*, 6: 93-107.

Sakai, A.K., Allendorf, F.W., Holt, J.S., Lodge, D.M., Molofsky, J., With, K.A., Baughman, S., Cabin, R.J., Cohen, J.E., Ellstrand, N.C., McCauley, D.E., O'Neil, P., Parker, I.M., Thompson, J.N. & Weller, S.G. (2001) The population biology of invasive species. *Annual Review of Ecology and Systematics*, 32: 305-332.

Sala, O.E., Chapin, F.S.I., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber–Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., LeRoy, N., Sykes, M.T., Walker, B.H., Walker, M. & Wall, D.H. (2000) Global biodiversity scenarios for the year 2100. *Science*, 287: 1770-1774.

SAS Institute Inc. (2000) *Statistics and Graphics Guide*. SAS Institute Inc.

Sax, D.F. (2002) Native and naturalized plant diversity are positively correlated in scrub communities of California and Chile. *Diversity and Distributions*, 8: 193-210.

Scott, J.K., & Panetta, F.D. (1993) Predicting the Australian weed status of southern African plants. *Journal of Biogeography*, 20: 87-93.

Seabloom, E.W., Williams, J.W., Slayback, D., Stoms, D.M., Viers, J.H. & Dobson, A.P. (2006) Human impacts, plant invasion, and imperiled species in California. *Ecological Applications*, 16: 1338-1350.

Seber, G.A.F. & Wild, C.J. (1989) *Nonlinear regression*. John Wiley and Sons, New York.

Settele, J., Hammen, V., Hulme, P.E., Karlson, U., Klotz, S., Kotarac, M., Kunin, W.E., Marion, G., O'Connor, M., Petanidou, T., Peterseon, K., Potts, S., Pritchard, H., Pyšek, P., Rounsevell, M., Spangenberg, J., Steffan–Dewenter, I., Sykes, M.T., Vighi, M., Zobel, M. & Kühn, I. (2005) ALARM: Assesing LArge scale environmental Risks for biodiversity with tested Methods. *GAIA – Ecological Perspectives in Science, Humanities, and Economics*, 14: 9-72.

Shigesada, N., Kawasaki, K. & Takeda, Y. (1995) Modeling stratified diffusion in biological invasions. *American Naturalist*, 146: 229-251.

Simberloff, D. (1981). Community effects of introduced species. In: *Biotic Crises in Ecological and Evolutionary Time*, (ed. by Nitecki, T.H.), pp. 53-81. Academic Press, New York.

Simberloff, D. (1986) Introduced insects: a biogeographic and systematic perspective. In: *Ecology of biological invasions of North America and Hawaii*, (ed. by Mooney, H. A. & Drake, J. A.), pp. 3-26. Wiley, New York.

Smith, H.A., Jonson, W.S. & Shonkwiler, J.S. (1999) The implications of variable or constant expansion rates in invasive weed infestations. *Weed Science*, 47: 62-66.

Sokal, R.R. & Rohlf, F.J. (1992) *Biometry*. Freeman, New York

Sol, D., Vilà, M. & Kühn, I. (2008) The comparative analysis of historical alien introductions. *Biological Invasions*, 10: 1119-1129.

Stadler, J., Mungai, G. & Brandl, R. (1998) Weed invasion in East Africa: insights from herbarium records. *African Journal of Ecology*, 36: 15-22.

Taylor, B.W. & Irwin, R.E. (2004) Linking economic activities to the distribution of exotic plants. *Proceedings of the National Academy of Science of the United States of America*, 101: 17725-17730.

Thuiller, W., Richardson, D., Rouget, M., Proches, S. & Wilson, J. (2006) Interactions between environment, species traits, and human uses describes patterns of plant invasions. *Ecology*, 87: 1755-1769.

Torrejón, F. & Cisternas, M. (2002) Araucanian ecological landscape disturbances by the mapuche assimilation of the Hispanic-Mediterranean farming (16^{th} and 17^{th} centuries). *Revista Chilena de Historia Natural*, 75: 729-736.

Trammell, M.A. & Butler, J.L. (1995) Effects of exotics plants on native ungulate use of habitat. *Journal of Wildlife Management*, 59: 808-816.

Trombulak, S. & Frissell, C. (2000) Review of ecological effects of roads on terrestrial and aquatic communities. *Conservation Biology*, 14: 18–30.

Tucker, K.C. & Richardson, D.M. (1995) An expert system for screening potentially invasive alien plants in South African Fynbos. *Journal of Environmental Management*, 44: 309-338.

Ugarte, E., Fuentes, N. & Klotz, S. (in press) European plants in southern South America, unwanted visitors?. In: *Atlas of Biodiversity Risks - from Europe to the globe, from stories to maps*, (ed. by Settele, J.). Pensoft, Sofia & Moscow.

Veblen, T.T., Schlegel, F.M. & Oltremari, J.V. (1983) Temperate broad-leaved evergreen forest of South America. In: *Temperate broad-leaved Forest*, (ed. by Ovington, J.D.), pp. 5-31. Elsevier Science Publisher, Amsterdam.

Vilà, M. & Pujadas, J. (2001) Land-use and socio-economic correlates of plant invasions in European and North African countries. *Biological Conservation*, 100: 397-401.

Vilà, M., Tessier, M., Suehs, C.M., Brundu, G., Carta, L., Galanidis, A., Lambdon, P., Manca, M., Médail, F., Moragues, E., Traveset, A., Troumbis, A.Y. & Hulme, P.E. (2006) Local and regional assessment of the impacts of plant invaders on vegetation structure and soil properties of Mediterranean islands. *Journal of Biogeography*, 33: 853-861.

Vitousek, P., Mooney, H., Lubchenco, J. & Melillo, J. (1997a) Human Domination of Earth's Ecosystems. *Science*, 277: 494-499.

Vitousek, P.M. (1990) Biological invasions and ecosystem processes: towards an integration of population biology and ecosystem studies. *Oikos*, 57: 7-13.

Vitousek, P.M. (1994) Beyond global warming: ecology and global change. *Ecology*, 75: 1861-1876.

Vitousek, P.M. & Walter, L.R. (1989) Biological invasions by *Myrica faya* in Hawaii: plant demography, nitrogen fixation, ecosystem effects. *Ecological Monographs*, 59: 247-265.

Vitousek, P.M., D'Antonio, C.M., Loope, L.L. & Westbrooks, R. (1996) Biological invasions as global environmental change. *American Scientist*, 84: 468-478.

Vitousek, P.M., D'Antonio, C.M., Loope, L., Rejmanek, M. & Westbrooks, R. (1997b) Introduced species: A significant component of human-caused global change. *New Zealand Journal of Ecology*, 21: 1-16.

Weber, E. (2003) *Invasive plant species of the world: a reference guide to environmental weeds*. CABI Publishing, Wallingford, UK.

Westbrooks, R.G. (1991) Plant protection issues I. A commentary on new weeds in the United States. *Weed Technology*, 5: 232-237.

Westphal, M., Browne, M., MacKinnon, K. & Noble, I. (2008) The link between international trade and the global distribution of invasive species. *Biological Invasions*, 10: 391-398.

Williamson, M. (1996) *Biological invasions*. Chapman and Hall, London, UK.

Williamson, M. (1999) Invasions. *Ecography*, 22: 5-12.

Williamson, M. H. & Fitter, A. (1996) The varying success of invaders. *Ecology*, 77: 1661-1666.

Willis, F., Moat, J. & Paton, A. (2003) Defining a role for herbarium data in Red List assessment: a case study of Plectranthus form eastern and southern tropical Africa. *Biodiversity and Conservation*, 12: 1537-1552.

Wu, S.H., Hsieh, C.F., Chaw, S.M. & Rejmánek, M. (2004) Plant invasions in Taiwan: Insights from the flora of casual and naturalized alien species. *Diversity and Distribution*, 10: 349-362.

Wu, S.H., Rejmánek, M., Grotkopp, E. & DiTomaso, M. (2005) Herbarium records, actual distribution, and critical attributes of invasive plants: genus *Crotalaria* in Taiwan. *Taxon*, 54: 133-138.

Yelenik, S.G., Stock, W.D. & Richardson, D. (2004) Ecosystem level impacts of invasive *Acacia saligna* in the South African Fynbos. *Restoration Ecology*, 12: 44-51.

Zamora, D.L., Thill, D.C. & Eplee, R.E. (1989) An eradication plan for plant invasions. *Weed Technology*, 3: 2-12.

Zuloaga, F. & Morrone, O. (1996) Catálogo de las plantas vasculares de la República Argentina I. Pteridophyta, Gymnospermae y Angiospermae (Monocotyledoneae). *Monographs in Systematics Botany of the Missouri Botanical Garden*, 60: 1-323.

Zuloaga, F. & Morrone, O (1999) Catálogo de las plantas vasculares de la República Argentina (Dicotyledoneae). *Monographs in Systematics Botany of the Missouri Botanical Garden*, 74: 1-1246.

Supplements

Acknowledgments / Agradecimientos

Along the process of this thesis I learned that the scientific carrier is a hard challenge, and sometimes ungrateful, but fortunately not solitary. Many people have contributed either directly or indirectly to this study. This thesis could not have been done without the help and support of them. It is a pleasure to thank all those who made this thesis possible.

First of all, I like to thank my advisor at the University of Concepción, Eduardo Ugarte, who first introduced me to the plant biology study. For his support in this thesis and past works, and for all those brain storming sessions we had together. All his help it was absolutely invaluable. I would like to express my gratitude to Stefan Klotz for being a great advisor. His ideas and tremendous support had a major influence on this thesis. He spends a lot of time helping me. I would like to thank him for giving me the chance to visit the Department of Community Ecology - UFZ and interesting conferences several times. I learned a lot during this time and I am convinced that this knowledge will help me in the future.

I would like to thank Ingolf Kühn for reviewing my manuscripts and the thesis, I am happy to have such a supportive co-supervisor at the UFZ. I enjoyed his interest in my research as well as the fruitful discussions. I would also like to thank Isabell Hensen, my advisor at the Martin-Luther University, for her supports in all the university concerns. She always took time out of her busy schedules to encouraged me to finish the PhD thesis.

It was a pleasure for me to work with all the wonderful people in the UFZ. I also wish to thank to Ellen Sellent, for her valuable assistance in all my problems during my visits to UFZ in Halle.

Every year that I visited Halle it was an adventure. From these travels I got more than a paper or thesis, I got friends. Many thank to Heike, Jan, Henrik, and Marten. I enjoyed Halle with them, the atmosphere, their friendship, and their support.

Last but not least, I wish to thank my family who always supported me. To my parents and brothers, who were always there for me and helped in any kind of troubles. Finally and most importantly, to my husband Alfredo for his loves and supports every day in my life.

This thesis has been supported by the EC within the FP 6 Integrated Project ALARM (Assessing LArge scale environmental Risks for biodiversity with tested Methods; GOCE-CT- 2003-506675; www.alarmproject.net; Settele *et al*. 2005). Their support is gratefully acknowledged.

Durante el proceso de esta tesis aprendí que la investigación es un trabajo muy difícil, a veces ingrato y amargo, pero afortunadamente no solitario. Mucha gente ha participado en la realización de esta tesis, directa e indirectamente, me han apoyado para seguir adelante. Es un placer para mí agradecer a todos aquellos que han hecho posible el desarrollo de esta tesis.

Primero que todo quiero agradecer a Eduardo Ugarte, quien me introdujo en el mundo del estudio de las plantas. Su particular modo de ver la vida y como enfrentar las dificultades son una gran herencia, y debo decir que son mas importantes que el aprendizaje teórico y practico que me entrego durante los años trabajando juntos.

Estoy enormemente agradecida del apoyo que Stefan Klotz me brindo antes y durante el desarrollo de esta tesis. Stefan creyó y confió en mí, me dio la oportunidad de conocer, trabajar, aprender y disfrutar de un enorme grupo de personas que trabajan en el Departamento de Ecología de Comunidades del instituto UFZ. Quiero agradecer también el apoyo de Ingolf Kühn, quien siempre tuvo mucha paciencia y tiempo para apoyarme en lo más difícil para mi, estadística. Siempre tuvo una palabra de aliento que me hizo sentir segura de las locuras que estaba haciendo. Igualmente quiero agradecer a Isabell Hensen, quien me acepto como su estudiante en esta empresa llamada tesis. Quiero agradecer su apoyo, ya que cada vez que recurrí a ella tuvo tiempo para orientarme en mis dudas.

Quiero señalar que estoy muy feliz y agradecida de haber tenido la oportunidad de trabajar en el instituto UFZ, ha sido una gran experiencia tanto en lo profesional como en lo personal. Quiero agradecer a Ellen Selent, secretaria del Departamento de Ecología de Comunidades, quien siempre me ayudo a resolver mis problemas estando en Halle y Concepción.

Cada año que viaje a Halle fue una verdadera aventura, de esos viajes he logrado obtener mas que un paper o una tesis, he logrado tener buenos amigos. Quiero agradecer el apoyo infinito que siempre me han entregado Heike, Jan, Henrik y Marten, sin ellos mi vida en Halle no hubiera sido lo mismo.

Finalmente quiero agradecer a mi familia, sin ellos todo lo que hago no seria lo mismo. A mis hermanos, quiero agradecer su incondicional apoyo en todas las locuras que emprendo aun no entendiendo bien de que se tratan. Gracias a mis padres Gricelda y Francisco, por todo el esfuerzo que hicieron para ayudarme en esta carrera un poco extraña y no siempre entendida. Y por ultimo quiero agradecer a mi esposo Alfredo, quiero agradecer su amor y apoyo infinito, no solo durante la realización de esta tesis, sino en cada día de mi vida.

Esta investigación, las asistencias a congresos y las estadías en Halle no hubieran sido posible sin el financiamiento entregado por el proyecto "ALARM" EC FP 6 Integrated Project (Assessing LArge scale environmental Risks for biodiversity with tested Methods; GOCE-CT-2003-506675; www.alarmproject.net; Settele *et al.* 2005).

Curriculum vitae

Contact information

Name: Nicol Elvira Fuentes Parada

Address: Pasaje Daniel Urrejola 35, Depto 301, Concepción, Chile

Phone: 56-41-2203418

e-mail: nfuentes@udec.cl

Personal details

Date of birth: 02.09.1977

City / Country: Parral, Chile

Marital status: Married

Education

1997-2002.1 University of Concepción, Bachelor of Science

2005-2009 PhD-thesis at the Helmholtz Centre for Environmental Research (UFZ), Department of Community Ecology (Stefan Klotz and Ingolf Kühn) and Deparment of Botany Universidad de Concepción (Eduardo Ugarte). Employed by EU – Project "ALARM" Assessing LArge scale environmental Risks for biodiversity with tested Methods (project no. GOCE-CT- 2003-506675).

Diploma thesis: El borde de camino como corredor de especies introducidas hacia un Parque Nacional.
Supervision: Dr. Eduardo Ugarte

PhD thesis: Alien plant invasion in Chile: history, drivers, and risks.

Supervision: Prof. Dr. Isabell Hensen, Dr. Stefan Klotz, Dr. Ingolf Kühn and Dr. Eduardo Ugarte.

List of publications

Fuentes, N., Ugarte, E. & Klotz, S. (2004) Flora asociada a bordes de camino en un transecto Este-Oeste en la VIII Región, Chile. *Boletín del Museo de Historia Natural*, **53**: 37-49.

Ugarte, E., **Fuentes**, **N**. & Klotz, S. (2004) Uso del suelo, vegetación y restauración ecosistémica. Una aproximación en escala intermedia para la cuenca del río Laja (Chile). *Terra-Autralis*, **49**: 115-128.

Fuentes, **N**., Ugarte, E., Kühn, I. & Klotz, S. (2008) Alien plants in Chile. Inferring invasion periods from herbarium records. *Biological Invasions*, **10**: 649–657.

Ugarte, E., **Fuentes**, **N**. & Klotz, S. European plant in southern South America, unwanted visitors?. In: *Atlas of Biodiversity Risks - from Europe to the globe, from stories to maps* (ed. by Settele, J.). Pensoft, Sofia & Moscow. (in press).

Fuentes, **N**. & Saldaña, A. R*eynoutria japonica* Houtt. (Polygonaceae) new record for the alien flora of Chile. (accepted in *Gayana Botanica*).

Contributions to conferences

Fuentes, **N**., Ugarte, E., Kühn, I. & Klotz, S. Alien plants in southern South America I . Historical perspective and global diversity. EURECO-GFO-Conference - Biodiversity in an ecosystem context. Leipzig, Germany 2008.

Fuentes, **N**., Ugarte, E. & Klotz, S. Alien plants in southern South America IV. Chile and Argentina, levels on the mutual risk of invasion. EURECO-GFO-Conference - Biodiversity in an ecosystem context. Leipzig, Germany 2008.

Fuentes, **N**., Ugarte, E. & Klotz, S. Periodos de invasión y factores asociados a la abundancia de especies de plantas introducidas en Chile. II Encuentro Universitario sobre Conservación y Manejo de Flora y Fauna Silvestre. Chillan, Chile 2007.

Fuentes, **N**., Ugarte, E. & Klotz, S. Anthropogenic and climatic factors determining density of alien plant species in Chile. The 4th European Conference of the working group NEOBIOTA on Biological Invasions. Vienna, Austria 2006.

Fuentes, **N**., Ugarte, E., Saldaña, A. & Klotz, S. Anthropogenic and climatic factors determining density of alien plant species in Chile. XV Reunión Anual de la Sociedad de Ecología de Chile. La Serena, Chile 2006.

Fuentes, **N**., Ugarte, E., Hensen, I. & Klotz, S. Uso de registros de Herbario para identificar periodos de invasión de plantas introducidas en Chile. XXX Jornadas Argentinas de Botánica. Rosario, Argentina 2006.

Fuentes, **N**., Ugarte, E. & Klotz, S. Reconstructing spread and pattern of invasive plants in Chile from herbarium records. 8th International Conference on the Ecology and Management of Alien Plant Invasion (EMAPI). Katowice, Poland 2005.

Fuentes, **N**. & Ugarte, E. Caminos como corredores de dispersión de plantas introducidas en la VIII Región, Chile. XVL Reunión anual de la Sociedad de Biología de Chile. Puyehue, Chile 2002.

Eigenständigkeitserklärung

Hiermit erkläre ich, dass diese Arbeit mit dem Titel "Alien plant invasion in Chile: history, drivers, and risks" bisher weder der Naturwissenschaftlichen Fakultät I - Biowissenschaftender Martin-Luther-Universität Halle-Wittenberg noch einer anderen wissenschaftlichen Einrichtung zum Zweck der Promotion vorgelegt wurde.

Ferner erkläre ich, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe verfasst sowie keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. Die den benutzten Werken wörtlich oder inhaltlich entnommenen Stellen wurden als solche von mir kenntlich gemacht.

Ich erkläre weiterhin, dass ich mich bisher noch nie um einen Doktorgrad beworben habe.

Halle (Saale), 2009

Declaration of own contributions to the original articles

Because several co-authors contributed to the original articles in the following the percentage of own work is displayed.

Chapter 2: Alien plants in Chile. Inferring invasion periods from herbarium records.

- -Data collection, acquisition, and improvement of the herbarium records: **Nicol Fuentes** (90%); Eduardo Ugarte (10%)
- -Statistical analysis: **Nicol Fuentes** (90%); Ingolf Kühn (10%)
- -Writing manuscript: **Nicol Fuentes** (60%); Eduardo Ugarte (20%); Ingolf Kühn (10%); Stefan Klotz (10%)

Chapter 3: The role of human habitat disturbances and climate gradient on alien plants density at provinces scale in Chile, South America.

- -Data collection and acquisition: **Nicol Fuentes** (100%)
- -Statistical analysis: **Nicol Fuentes** (80%); Ingolf Kühn (20%)
- -Writing manuscript: **Nicol Fuentes** (70%); Eduardo Ugarte (10%); Ingolf Kühn (10%); Stefan Klotz (10%)

Chapter 4: Alien plants in southern South America. A framework for evaluation and management of mutual risk of invasion between Chile and Argentina.

- -Data collection, acquisition, and fulfill weed risk assessment form: **Nicol Fuentes** (70%); Eduardo Ugarte (30%)
- -Statistical analysis: **Nicol Fuentes** (90%); Ingolf Kühn (10%)
- -Writing manuscript: **Nicol Fuentes** (70%); Eduardo Ugarte (10%); Ingolf Kühn (10%); Stefan Klotz (10%)

Appendix I

Appendix I Alien species *rejected* in each category based on the risk level assignments according to presence/absence in countries and road margins and sorted by expansion on the territory index (ET-index; number of provinces divided by number of years of residence for each species). All species were classified into ranks (5 very high; 4 high; 3 medium; 2 low; 1very low). NYR = number of years of residence, NP = number of provinces, ch = Chile, ar = Argentina, A = agricultural areas, E = environmental areas, and B = both areas; nd = non data.

Exclusive to Chile - along roads	rank	ET-index	WRA-ChAr	NYR	NP	area affected
Parentucellia viscosa	5	0.21	12	48	10	A
Verbascum virgatum	5	0.19	17	112	21	B
Rubus ulmifolius	5	0.16	28	110	18	A
Veronica serpyllifolia	5	0.15	15	112	17	A
Carduus nutans	5	0.11	23	47	5	E
Cynosurus echinatus	5	0.10	13	126	13	A
Verbascum thapsus	5	0.10	19	126	13	B
Phalaris canariensis	5	0.10	17	82	8	A
Acacia dealbata	5	0.10	19	126	12	E
Spergularia rubra	5	0.09	13	161	15	A
Rubus constrictus	5	0.09	25	79	7	B
Phalaris aquatica	5	0.09	14	81	7	E
Rosa rubiginosa	5	0.08	24	132	11	E
Boerhavia diffusa	5	0.07	15	116	8	A
Cytisus striatus	5	0.06	17	110	7	E

Tolpis barbata	5	0.06	12	126	7	A
Geranium robertianum	5	0.05	12	161	8	A
Juncus bufonius	5	0.04	12	153	6	A
Robinia pseudoacacia	5	0.04	15	110	4	E
Lotus uliginosus	5	0.03	16	160	5	B
Petrorhagia prolifera	5	0.03	13	65	2	E
Anthemis arvensis	5	0.02	14	103	2	A

Exclusive to Chile - not along roads	**rank**	**ET-index**	**WRA-ChAr**	**NYR**	**NP**	**area affected**
Hordeum marinum	4	0.65	16	20	13	E
Rosa canina	4	0.33	19	6	2	E
Veronica anagallis-aquatica	4	0.27	13	110	30	E
Veronica peregrina	4	0.27	13	11	3	A
Galenia pubescens	4	0.25	12	4	1	E
Veronica persica	4	0.24	13	96	23	A
Pennisetum clandestinum	4	0.21	18	19	4	B
Bromus rigidus	4	0.21	22	82	17	A
Setaria pumila	4	0.20	19	25	5	A
Polygonum campanulatum	4	0.20	12	15	3	E
Ranunculus arvensis	4	0.19	13	16	3	A
Cyperus difformis	4	0.18	11	22	4	A
Sherardia arvensis	4	0.18	11	91	16	A
Petrorhagia dubia	4	0.17	13	71	12	A

Oenothera rosea	4	0.17	10	77	13	A
Mentha suaveolens	4	0.17	13	89	15	A
Papaver hybridum	4	0.17	15	6	1	A
Orobanche ramosa	4	0.16	21	19	3	A
Eleocharis acicularis	4	0.15	25	20	3	E
Poa annua	4	0.15	26	151	22	A
Papaver dubium	4	0.14	14	7	1	A
Emex spinosa	4	0.14	13	7	1	E
Amaranthus hybridus	4	0.14	21	156	22	E
Polypogon monspeliensis	4	0.14	18	151	21	E
Leontodon hirtus	4	0.14	13	29	4	A
Torilis arvensis	4	0.13	10	15	2	A
Modiola caroliniana	4	0.13	10	159	21	A
Alisma lanceolatum	4	0.13	17	77	10	E
Vicia benghalensis	4	0.13	12	108	14	A
Polypogon viridis	4	0.13	14	78	10	A
Malva assurgentiflora	4	0.12	11	57	7	E
Eschscholtzia californica	4	0.12	12	124	15	B
Eremocarpus setigerus	4	0.12	15	25	3	A
Veronica arvensis	4	0.12	15	110	13	A
Datura inoxia	4	0.12	22	17	2	A
Phleum pratense	4	0.12	20	85	10	E
Kickxia elatine	4	0.12	11	34	4	A

Euphorbia serpens	4	0.11	14	61	7	A
Poa bulbosa	4	0.11	17	9	1	B
Knautia integrifolia	4	0.11	11	18	2	A
Acacia melanoxylon	4	0.11	18	82	9	B
Trifolium incarnatum	4	0.11	10	73	8	E
Alisma plantago-aquatica	4	0.11	17	85	9	A
Taeniatherum caput-medusae	4	0.11	11	19	2	A
Barbarea verna	4	0.10	15	77	8	A
Iris pseudacorus	4	0.10	12	10	1	E
Malva dendromorpha	4	0.10	10	70	7	E
Valerianella rimosa	4	0.10	10	10	1	B
Datura stramonium	4	0.10	21	156	15	A
Hirschfeldia incana	4	0.10	11	42	4	A
Echinochloa colona	4	0.09	16	109	10	A
Rumex obtusifolius	4	0.09	12	81	7	A
Vicia hirsuta	4	0.08	13	108	9	A
Portulaca oleracea	4	0.08	11	158	13	A
Sambucus nigra	4	0.08	14	76	6	E
Solanum nigrum	4	0.08	21	156	12	E
Nymphaea alba	4	0.08	11	13	1	E
Orobanche minor	4	0.08	23	53	4	A
Erodium botrys	4	0.08	16	159	12	E
Vicia villosa	4	0.07	16	108	8	A

Azolla filiculoides	4	0.07	21	151	11	E
Echinochloa crus-pavonis	4	0.07	10	151	11	A
Euphorbia cyathophora	4	0.07	11	14	1	A
Mecardonia procumbens	4	0.07	11	14	1	A
Coronopus didymus	4	0.07	13	159	11	A
Glechoma hederacea	4	0.07	11	74	5	A
Polygonum hydropiper	4	0.07	23	45	3	E
Equisetum bogotense	4	0.07	10	151	10	A
Piptatherum miliaceum	4	0.07	11	46	3	A
Physalis pubescens	4	0.06	17	156	10	E
Panicum capillare	4	0.06	17	79	5	A
Plantago coronopus	4	0.06	15	65	4	E
Paspalum paspalodes	4	0.06	19	151	9	B
Paspalum vaginatum	4	0.06	11	151	9	B
Agropyron cristatum	4	0.06	15	17	1	E
Senecio angulatus	4	0.06	14	86	5	E
Verbena litoralis	4	0.06	11	156	9	A
Bidens laevis	4	0.06	11	157	9	A
Erigeron karwinskianus	4	0.06	12	71	4	A
Setaria adhaerens	4	0.06	15	18	1	A
Myosotis latifolia	4	0.06	12	72	4	E
Vicia tetrasperma	4	0.06	11	108	6	E
Vicia tenuissima	4	0.06	10	18	1	A

Galium murale	4	0.05	13	91	5	E
Phragmites australis	4	0.05	23	151	8	E
Echinochloa crus-galli	4	0.05	14	151	8	A
Bromus squarrosus	4	0.05	10	19	1	A
Polypogon maritimus	4	0.05	10	38	2	E
Lathyrus sativus	4	0.05	10	59	3	E
Cenchrus myosuroides	4	0.05	10	80	4	A
Ranunculus parviflorus	4	0.05	10	60	3	A
Mesembryanthemum crystallinum	4	0.05	13	124	6	B
Glyceria fluitans	4	0.05	10	62	3	E
Valerianella eriocarpa	4	0.05	10	62	3	A
Stachys arvensis	4	0.05	10	42	2	A
Sium latifolium	4	0.05	17	64	3	E
Cyperus eragrostis	4	0.05	17	151	7	A
Hordeum secalinum	4	0.05	11	151	7	E
Salvinia auriculata	4	0.05	16	44	2	E
Oxalis pes-caprae	4	0.04	14	89	4	B
Brassica napus	4	0.04	14	159	7	A
Oxalis corniculata	4	0.04	13	159	7	A
Cyperus alternifolius	4	0.04	14	49	2	A
Nasturtium officinale	4	0.04	12	25	1	A
Ornithopus sativus	4	0.04	10	75	3	A
Sporobolus virginicus	4	0.04	10	50	2	E

Potamogeton pusillus	4	0.04	21	153	6	E
Linaria vulgaris	4	0.04	11	130	5	A
Solanum eleagnifolium	4	0.04	10	156	6	A
Veronica beccabunga	4	0.04	10	26	1	E
Poa nemoralis	4	0.04	12	53	2	A
Papaver somniferum	4	0.04	15	160	6	A
Spergularia marina	4	0.04	12	80	3	E
Trifolium striatum	4	0.04	14	108	4	A
Lotus angustissimus	4	0.04	13	27	1	E
Eragrostis pilosa	4	0.04	24	82	3	A
Acacia horrida	4	0.04	13	55	2	A
Euphorbia hirta	4	0.03	17	59	2	A
Juncus effusus	4	0.03	18	90	3	E
Selaginella apoda	4	0.03	11	30	1	A
Verbesina encelioides	4	0.03	9	60	2	A
Hypericum androsaemum	4	0.03	13	124	4	E
Parapholis strigosa	4	0.03	12	63	2	E
Schizachyrium sanguineum	4	0.03	13	64	2	A
Cenchrus incertus	4	0.03	16	66	2	A
Sida spinosa	4	0.03	10	68	2	A
Phalaris arundinacea	4	0.03	16	73	2	A
Veronica scutellata	4	0.03	14	73	2	E
Veronica officinalis	4	0.03	10	73	2	A

Salix viminalis	4	0.03	12	76	2	B
Cyperus rotundus	4	0.03	10	76	2	A
Zannichellia palustris	4	0.03	13	153	4	E
Eichornia crassipes	4	0.02	14	88	2	E
Reseda phyteuma	4	0.02	10	44	1	A
Galium tricornutum	4	0.02	17	46	1	A
Chloris virgata	4	0.02	16	50	1	B
Dolichos lignosus	4	0.02	15	50	1	E
Crotalaria incana	4	0.02	11	50	1	B
Chenopodium ficifolium	4	0.02	13	156	3	A
Ornithopus pinnatus	4	0.02	10	52	1	E
Papaver rhoeas	4	0.02	17	160	3	A
Hieracium pilosella	4	0.02	18	54	1	B
Senna bicapsularis	4	0.02	11	61	1	E
Sida rhombifolia	4	0.02	11	63	1	A
Reseda lutea	4	0.02	11	65	1	A
Scirpus mucronatus	4	0.01	18	67	1	A
Phalaris caroliniana	4	0.01	16	73	1	E
Passiflora foetida	4	0.01	17	75	1	A
Chloris radiata	4	0.01	12	75	1	A
Diplachne uninervia	4	0.01	12	151	2	E
Pennisetum villosum	4	0.01	10	77	1	B
Amaranthus viridis	4	0.01	24	156	2	A

Ipomoea purpurea	4	0.01	12	156	2	A
Bidens pilosa	4	0.01	19	157	2	E
Miscanthus sinensis	4	0.01	11	80	1	E
Waltheria indica	4	0.01	11	80	1	A
Callitriche terrestris	4	0.01	14	118	1	B
Panicum miliaceum	4	0.01	18	124	1	A
Setaria parviflora	4	0.01	16	151	1	A
Cyperus articulatus	4	0.01	11	151	1	A
Pseudognaphalium luteoalbum	4	0.01	10	157	1	E
Hibiscus trionum	4	0.01	10	159	1	A

Exclusive to Argentina- not along roads	**rank**	**ET-index**	**WRA-ChAr**	**NYR**	**NP**	**area affected**
Geranium carolinianum	4	1.22	16	9	11	A
Diplotaxis tenuifolia	4	0.62	10	21	13	A
Rorippa palustris	4	0.60	20	20	12	A
Chenopodium giganteum	4	0.50	11	8	4	A
Morus alba	4	0.35	14	20	7	A
Artemisia verlotiorum	4	0.33	22	42	14	A
Brassica juncea	4	0.33	12	18	6	A
Silene antirrhina	4	0.32	10	38	12	E
Tordylium maximum	4	0.30	11	10	3	B
Melia azedarach	4	0.29	19	28	8	E
Erysimum repandum	4	0.29	16	21	6	A

Vaccaria pyramidata	4	0.29	13	21	6	A
Euphorbia dentata	4	0.28	17	43	12	A
Sarcocornia perennis	4	0.28	10	58	16	E
Arenaria serpyllifolia	4	0.25	10	20	5	A
Euphorbia hyssopifolia	4	0.25	10	28	7	A
Senecio madagascariensis	4	0.24	15	25	6	A
Mentha x rotundifolia	4	0.23	20	26	6	E
Lycopsis arvensis	4	0.22	16	9	2	E
Cucumis anguria	4	0.22	17	46	10	A
Atriplex heterosperma	4	0.22	10	23	5	E
Euphorbia spathulata	4	0.21	11	28	6	E
Centunculus minimus	4	0.21	10	63	13	E
Fumaria officinalis	4	0.20	16	44	9	A
Chenopodium carinatum	4	0.20	14	30	6	A
Plantago arenaria	4	0.20	12	10	2	A
Bassia scoparia	4	0.20	11	60	12	B
Opuntia ficus-indica	4	0.20	14	86	17	E
Carduus tenuiflorus	4	0.19	20	42	8	B
Lepidium perfoliatum	4	0.19	16	21	4	E
Malcolmia africana	4	0.19	15	21	4	E
Mesembryanthemum nodiflorum	4	0.19	15	21	4	E
Camelina microcarpa	4	0.19	13	21	4	A
Euphorbia marginata	4	0.18	16	28	5	A

Elaeagnus angustifolia	4	0.18	24	17	3	E
Neonotonia wightii	4	0.18	10	17	3	B
Cuscuta pentagona	4	0.17	16	58	10	A
Coreopsis lanceolata	4	0.17	15	24	4	A
Sinapis arvensis	4	0.17	15	18	3	E
Artemisia annua	4	0.17	11	42	7	A
Tragopogon dubius	4	0.17	11	42	7	E
Citrullus lanatus	4	0.17	10	36	6	A
Leonurus sibiricus	4	0.16	11	70	11	A
Pyracantha angustifolia	4	0.14	14	14	2	E
Silene pratensis	4	0.14	10	21	3	E
Monolepis nuttalliana	4	0.13	11	38	5	A
Tithonia tubaeformis	4	0.13	15	31	4	A
Tithonia rotundifolia	4	0.13	12	31	4	A
Lepidium densiflorum	4	0.13	14	8	1	A
Sesbania bispinosa	4	0.13	12	16	2	A
Centaurea cyanus	4	0.12	13	49	6	A
Agrimonia parviflora	4	0.12	15	34	4	A
Lithospermum arvense	4	0.12	14	78	9	E
Fragaria vesca	4	0.11	16	18	2	A
Amorpha fruticosa	4	0.11	14	18	2	E
Tanacetum balsamita	4	0.11	13	27	3	A
Ipomoea quamoclit	4	0.11	11	46	5	A

Heterotheca latifolia	4	0.11	12	28	3	B
Tamarix gallica	4	0.11	10	56	6	A
Lepidium virginicum	4	0.11	19	19	2	E
Holosteum umbellatum	4	0.11	13	38	4	A
Artemisia douglasiana	4	0.11	11	38	4	E
Salix fragilis	4	0.10	18	48	5	E
Carduus acanthoides	4	0.10	22	79	8	B
Lupinus polyphyllus	4	0.10	19	40	4	E
Chorispora tenella	4	0.10	12	41	4	A
Canavalia ensiformis	4	0.10	9	41	4	A
Neslia paniculata	4	0.10	9	21	2	A
Silene dioica	4	0.10	9	21	2	A
Petrorhagia nanteuilii	4	0.10	9	21	2	E
Desmodium tortuosum	4	0.09	13	53	5	A
Campsis radicans	4	0.09	13	11	1	E
Acroptilon repens	4	0.08	13	61	5	A
Polygonum minus	4	0.08	19	49	4	A
Centaurea iberica	4	0.08	16	49	4	A
Parietaria officinalis	4	0.08	12	38	3	A
Herniaria hirsuta	4	0.08	11	38	3	E
Reseda luteola	4	0.08	10	38	3	A
Carpobrotus edulis	4	0.08	15	13	1	E
Coriandrum sativum	4	0.08	12	39	3	A

Lavatera arborea	4	0.08	16	40	3	E
Helianthus laetiflorus	4	0.07	11	27	2	A
Euphorbia thymifolia	4	0.07	10	28	2	A
Citrullus colocynthis	4	0.07	13	43	3	A
Gleditsia triacanthos	4	0.07	24	29	2	E
Camelina sativa	4	0.07	14	58	4	A
Salvia verbenaca	4	0.07	17	61	4	E
Arctotis stoechadifolia	4	0.06	13	31	2	A
Cucurbita pepo	4	0.06	11	31	2	A
Centaurea nigrescens	4	0.06	9	31	2	A
Centaurea diffusa	4	0.06	23	47	3	A
Dipsacus fullonum	4	0.06	22	48	3	E
Gaura parviflora	4	0.06	11	33	2	A
Scorzonera laciniata	4	0.06	10	34	2	E
Lotus suaveolens	4	0.06	10	35	2	E
Clerodendrum philippinum	4	0.06	17	36	2	E
Grevillea robusta	4	0.06	13	18	1	A
Fumaria bastardii	4	0.06	10	18	1	E
Lamium purpureum	4	0.05	19	56	3	E
Crepis foetida	4	0.05	15	38	2	B
Hedera helix	4	0.05	21	39	2	E
Cardaria chalepensis	4	0.05	21	60	3	B
Nepeta cataria	4	0.05	16	40	2	E

Amaranthus blitoides	4	0.05	12	40	2	A
Lepidium latifolium	4	0.05	28	21	1	E
Sinapis alba	4	0.05	17	21	1	E
Arabidopsis thaliana	4	0.05	14	21	1	A
Barbarea vulgaris	4	0.05	14	21	1	A
Tragopogon pratensis	4	0.05	12	42	2	A
Malcolmia maritima	4	0.05	12	21	1	B
Amaranthus dubius	4	0.05	11	21	1	A
Lepidium pinnatifidum	4	0.05	11	21	1	E
Stellaria graminea	4	0.05	10	21	1	A
Iberis amara	4	0.05	9	21	1	A
Trifolium spadiceum	4	0.05	9	21	1	E
Epilobium paniculatum	4	0.05	14	22	1	A
Fumaria densiflora	4	0.05	12	44	2	A
Campanula rotundifolia	4	0.05	10	22	1	A
Antirrhinum majus	4	0.04	12	45	2	A
Medicago truncatula	4	0.04	9	68	3	E
Montanoa bipinnatifida	4	0.04	20	23	1	E
Ipomoea tricolor	4	0.04	16	46	2	A
Sisymbrium runcinatum	4	0.04	13	23	1	A
Asclepias fruticosa	4	0.04	11	23	1	A
Sisymbrium erysimoides	4	0.04	9	23	1	B
Lathyrus latifolius	4	0.04	21	70	3	E

Cylindropuntia tunicata	4	0.04	9	47	2	B
Kalanchoe pinnata	4	0.04	15	24	1	A
Acer negundo	4	0.04	13	48	2	A
Polygonum amphibium	4	0.04	17	49	2	E
Rorippa dubia	4	0.04	9	50	2	A
Helianthus annuus	4	0.04	19	76	3	A
Helianthus petiolaris	4	0.04	14	76	3	A
Chondrilla juncea	4	0.04	21	28	1	A
Ratibida columnifera	4	0.04	9	28	1	E
Rhamnus catharticus	4	0.03	21	59	2	E
Lepidium sativum	4	0.03	20	60	2	B
Cardaria pubescens	4	0.03	13	60	2	A
Emilia fosbergii	4	0.03	9	30	1	E
Rosa micrantha	4	0.03	10	65	2	B
Descurainia pinnata	4	0.03	15	66	2	A
Hieracium murorum	4	0.03	9	34	1	E
Thunbergia alata	4	0.03	12	36	1	E
Lamium hybridum	4	0.03	19	37	1	E
Erysimum cheiranthoides	4	0.03	14	37	1	A
Cycloloma atriplicifolium	4	0.03	18	38	1	E
Medicago scutellata	4	0.03	17	38	1	E
Phyllanthus tenellus	4	0.03	17	38	1	E
Trifolium resupinatum	4	0.03	17	38	1	A

Humulus scandens	4	0.03	16	38	1	E
Coronilla varia	4	0.03	14	38	1	A
Prunus mahaleb	4	0.03	10	38	1	E
Geranium rotundifolium	4	0.03	15	39	1	A
Caucalis platycarpos	4	0.03	11	39	1	A
Oenanthe globulosa	4	0.03	11	39	1	A
Onopordum nervosum	4	0.03	10	39	1	E
Anchusa officinalis	4	0.03	10	78	2	A
Bupleurum tenuissimum	4	0.03	9	39	1	A
Tecoma capensis	4	0.03	9	40	1	E
Gaillardia aristata	4	0.02	10	42	1	B
Salvia reflexa	4	0.02	15	44	1	A
Amaranthus bouchonii	4	0.02	10	44	1	A
Ranunculus falcatus	4	0.02	14	46	1	A
Sphaerophysa salsula	4	0.02	16	53	1	A
Melilotus messanensis	4	0.02	13	53	1	A
Colutea arborescens	4	0.02	10	53	1	E
Gynura aurantiaca	4	0.02	9	54	1	E
Knautia arvensis	4	0.02	13	56	1	A
Cuscuta epilinum	4	0.02	12	58	1	A
Suaeda fruticosa	4	0.02	11	60	1	E
Celosia argentea	4	0.02	16	64	1	A
Zygophyllum fabago	4	0.02	10	65	1	A

Molucella laevis	4	0.02	12	66	1	A
Glinus lotoides	4	0.01	11	79	1	A
Phytolacca americana	4	0.01	11	80	1	E
Vicia cracca	4	0.01	10	91	1	E
Bromus inermis	4	nd	24	nd	nd	A
Eragrostis superba	4	nd	24	nd	nd	A
Oryza rufipogon	4	nd	23	nd	nd	A
Alopecurus aequalis	4	nd	22	nd	nd	A
Bothriochloa ischaemum	4	nd	22	nd	nd	A
Bromus rubens	4	nd	22	nd	nd	A
Opuntia monacantha	4	nd	20	nd	nd	E
Bambusa vulgaris	4	nd	18	nd	nd	E
Digitaria ternata	4	nd	16	nd	nd	A
Agrostis nebulosa	4	nd	15	nd	nd	E

In both countries - along roads in Chile and Argentina	**rank**	**ET-index-ch**	**ET-index-ar**	**WRA-ChAr**	**NYR-ch**	**NYR-ar**	**NP-ch**	**NP-ch**	**area affected**
Plantago lanceolata	3	0.32	1.08	15	97	12	31	13	E
Bromus hordeaceus	3	0.27	nd	14	85	nd	23	nd	A
Hypochaeris radicata	3	0.23	0.2	15	102	44	23	9	E
Echium vulgare	3	0.21	0.01	16	100	80	21	1	B
Erodium cicutarium	3	0.2	0.19	18	161	95	33	18	B
Rumex acetosella	3	0.19	0.23	21	156	40	30	9	E
Dactylis glomerata	3	0.18	nd	20	97	nd	17	nd	E

Trifolium repens	3	0.17	0.78	19	110	23	19	18	A
Marrubium vulgare	3	0.16	0.5	15	158	28	26	14	E
Holcus lanatus	3	0.16	nd	19	132	nd	21	nd	B
Convolvulus arvensis	3	0.16	0.23	12	159	48	25	11	A
Aira caryophyllea	3	0.14	nd	14	153	nd	22	nd	E
Agrostis capillaris	3	0.14	nd	24	93	nd	13	nd	A
Cirsium vulgare	3	0.14	0.48	24	132	44	18	21	E
Hypericum perforatum	3	0.13	0.1	19	111	41	14	4	E
Taraxacum officinale	3	0.12	0.55	13	132	44	16	24	A
Avena barbata	3	0.12	nd	13	153	nd	18	nd	A
Lactuca serriola	3	0.11	0.34	14	102	44	11	15	A
Cerastium glomeratum	3	0.1	0.57	15	161	23	16	13	A
Prunella vulgaris	3	0.07	0.1	12	126	77	9	8	A
Hordeum jubatum	3	0.06	nd	12	52	nd	3	nd	A
Bromus tectorum	3	0.03	nd	11	159	nd	4	nd	B

In both countries-not along roads	**rank**	**ET-index-ch**	**ET-index-ar**	**WRA-ChAr**	**NYR-ch**	**NP-ch**	**NYR-ar**	**NP-ar**	**area affected**
Euphorbia maculata	1	0.39	0.46	18	18	7	28	13	A
Datura ferox	1	0.38	0.09	17	24	9	46	4	A
Euphorbia peplus	1	0.30	0.46	18	89	27	28	13	A
Picris echioides	1	0.27	0.12	21	77	21	42	5	A
Raphanus raphanistrum	1	0.26	0.17	17	68	18	18	3	E
Plantago major	1	0.26	1.10	16	73	19	10	11	A

Camellina alyssum	1	0.25	0.03	10	4	1	58	2	A
Polygonum aviculare	1	0.23	0.49	10	154	35	49	24	E
Rapistrum rugosum	1	0.22	0.95	11	77	17	21	20	A
Melilotus albus	1	0.22	0.67	15	77	17	21	14	E
Leontodon saxatilis	1	0.20	nd	12	70	14	nd	nd	A
Carduus thoermeri	1	0.20	0.38	22	5	1	42	16	A
Crepis pulchra	1	0.20	0.03	19	15	3	38	1	A
Medicago sativa	1	0.20	0.72	17	158	31	18	13	A
Carduus pycnocephalus	1	0.19	0.04	14	77	15	79	3	E
Trifolium glomeratum	1	0.19	0.10	10	83	16	21	2	A
Fallopia convolvulus	1	0.19	nd	15	73	14	nd	nd	A
Galium aparine	1	0.19	0.50	11	157	30	24	12	E
Chamomilla suaveolens	1	0.19	0.17	18	102	19	12	2	A
Chenopodium album	1	0.19	0.45	22	156	29	38	17	E
Melilotus indicus	1	0.18	0.81	22	158	29	21	17	B
Bartsia trixago	1	0.18	0.13	13	56	10	15	2	A
Agrostis stolonifera	1	0.18	nd	18	68	12	nd	nd	A
Sorghum halepense	1	0.17	nd	23	81	14	nd	nd	A
Centaurea melitensis	1	0.17	0.22	14	157	27	95	21	A
Bidens aurea	1	0.17	0.01	15	64	11	68	1	E
Rumex conglomeratus	1	0.17	0.29	14	88	15	38	11	E
Euphorbia platyphyllos	1	0.17	0.07	18	71	12	28	2	A
Capsella bursa-pastoris	1	0.16	1.10	12	159	26	21	23	A

Cotula coronopifolia	1	0.16	0.14	22	148	24	44	6	A
Lapsana communis	1	0.16	0.07	11	100	16	42	3	A
Anthemis cotula	1	0.16	0.43	14	157	25	42	18	A
Sonchus asper	1	0.16	0.38	15	157	25	42	16	A
Rostraria cristata	1	0.16	nd	19	89	14	nd	nd	A
Polygonum persicaria	1	0.16	0.39	18	154	24	49	19	E
Spergula arvensis	1	0.15	0.21	13	110	17	38	8	A
Atriplex semibaccata	1	0.15	0.78	12	78	12	23	18	E
Mentha pulegium	1	0.15	0.31	11	156	24	26	8	A
Anagallis arvensis	1	0.15	0.21	15	156	24	63	13	A
Crepis capillaris	1	0.15	0.21	13	124	19	42	9	A
Conium maculatum	1	0.15	0.21	14	157	24	39	8	A
Vulpia bromoides	1	0.15	nd	22	151	23	nd	nd	E
Trifolium campestre	1	0.15	0.03	13	108	16	37	1	A
Silene gallica	1	0.14	0.26	15	159	23	38	10	A
Lamium amplexicaule	1	0.14	0.22	24	97	14	37	8	A
Myosotis arvensis	1	0.14	0.11	12	71	10	28	3	A
Cichorium intybus	1	0.14	0.21	11	157	22	42	9	E
Hypochaeris aff glabra	1	0.14	0.10	13	100	14	42	4	A
Hordeum murinum	1	0.14	nd	10	151	21	nd	nd	A
Lupinus arboreus	1	0.14	0.14	18	124	17	21	3	E
Chenopodium murale	1	0.13	0.32	21	156	21	38	12	A
Poa pratensis	1	0.13	nd	10	151	20	nd	nd	E

Atriplex patula	1	0.13	0.04	13	38	5	23	1	A
Fumaria agraria	1	0.13	0.08	17	160	21	38	3	A
Briza minor	1	0.13	nd	14	130	17	nd	nd	A
Rumex crispus	1	0.13	0.42	17	154	20	38	16	E
Sonchus oleraceus	1	0.13	0.48	18	157	20	42	20	E
Daucus carota	1	0.13	0.08	18	157	20	39	3	B
Lolium perenne	1	0.13	nd	16	151	19	nd	nd	B
Lolium multiflorum	1	0.13	nd	12	151	19	nd	nd	A
Senecio vulgaris	1	0.13	0.07	22	151	19	56	4	A
Stellaria media	1	0.13	0.61	12	159	20	38	23	A
Erodium moschatum	1	0.13	0.18	21	159	20	39	7	A
Arundo donax	1	0.12	nd	12	57	7	nd	nd	E
Lotus tenuis	1	0.12	0.02	16	58	7	53	1	A
Sonchus tenerrimus	1	0.12	0.02	13	141	17	42	1	A
Medicago lupulina	1	0.12	0.45	11	158	19	53	24	A
Brassica rapa	1	0.12	1.10	10	159	19	21	23	A
Euphorbia helioscopia	1	0.12	0.14	13	67	8	28	4	A
Sisymbrium irio	1	0.12	1.00	14	76	9	23	23	A
Urtica urens	1	0.12	0.50	15	154	18	38	19	A
Tanacetum vulgare	1	0.12	0.26	15	86	10	34	9	A
Ranunculus repens	1	0.12	0.07	23	130	15	54	4	B
Echium plantagineum	1	0.11	0.12	12	70	8	78	9	E
Polycarpon tetraphyllum	1	0.11	0.24	18	158	18	38	9	B

Trifolium arvense	1	0.11	0.10	14	79	9	21	2	A
Lolium rigidum	1	0.11	nd	13	81	9	nd	nd	A
Geranium pusillum	1	0.11	0.44	11	9	1	9	4	A
Rumex longifolius	1	0.11	0.05	23	73	8	21	1	E
Cotula australis	1	0.11	0.24	21	102	11	42	10	A
Vicia sativa	1	0.11	0.05	17	158	17	38	2	A
Sisymbrium officinale	1	0.11	0.74	14	159	17	23	17	A
Catapodium rigidum	1	0.10	nd	14	80	8	nd	nd	A
Brachypodium distachyon	1	0.10	nd	13	30	3	nd	nd	A
Leucanthemum vulgare	1	0.10	0.30	10	130	13	27	8	A
Thlaspi arvense	1	0.10	0.14	16	20	2	21	3	A
Trifolium subterraneum	1	0.10	0.03	12	31	3	38	1	E
Salsola kali	1	0.10	0.75	15	156	15	8	6	A
Raphanus sativus	1	0.09	1.06	17	159	15	18	19	A
Anthriscus caucalis	1	0.09	0.08	10	106	10	12	1	E
Bromus diandrus	1	0.09	nd	17	86	8	nd	nd	E
Arctium minus	1	0.09	0.18	10	76	7	44	8	A
Senecio sylvaticus	1	0.09	0.05	18	88	8	56	3	A
Festuca arundinacea	1	0.09	nd	10	101	9	nd	nd	A
Saponaria officinalis	1	0.09	0.32	24	124	11	38	12	A
Cardaria draba	1	0.09	nd	13	68	6	nd	nd	E
Scleranthus annuus	1	0.09	0.07	10	68	6	44	3	A
Hedypnois cretica	1	0.09	0.05	10	102	9	42	2	A

Centaurea calcitrapa	1	0.09	0.31	12	80	7	49	15	E
Myosotis discolor	1	0.09	0.11	12	69	6	28	3	A
Rumex obtusifolius	1	0.09	0.37	13	81	7	38	14	A
Digitaria sanguinalis	1	0.08	nd	12	132	11	nd	nd	A
Rumex acetosa	1	0.08	0.18	11	12	1	22	4	A
Silybum marianum	1	0.08	0.36	22	157	13	42	15	E
Setaria verticillata	1	0.08	nd	16	109	9	nd	nd	A
Teline monspessulana	1	0.08	nd	17	158	13	nd	nd	E
Lagurus ovatus	1	0.08	nd	18	124	10	nd	nd	A
Bellis perennis	1	0.08	0.06	12	124	10	34	2	A
Cynodon dactylon	1	0.08	nd	11	151	12	nd	nd	A
Fumaria capreolata	1	0.08	0.16	14	166	13	38	6	E
Anthoxanthum odoratum	1	0.08	nd	13	130	10	nd	nd	E
Amaranthus retroflexus	1	0.08	0.08	21	156	12	39	3	A
Schismus barbatus	1	0.08	nd	16	79	6	nd	nd	E
Ulex europaeus	1	0.08	0.11	21	158	12	38	4	E
Leontodon autumnalis	1	0.07	0.04	21	54	4	25	1	A
Fumaria parviflora	1	0.07	0.20	17	136	10	44	9	A
Geranium molle	1	0.07	0.21	13	109	8	39	8	A
Ricinus communis	1	0.07	0.23	11	154	11	40	9	E
Senecio mikanioides	1	0.07	0.04	10	56	4	48	2	A
Torilis nodosa	1	0.07	0.03	15	157	11	39	1	A
Distichlis spicata	1	0.07	nd	11	151	10	nd	nd	A

Polygonum lapathifolium	1	0.06	0.37	29	154	10	49	18	A
Melissa officinalis	1	0.06	0.30	22	156	10	30	9	B
Scabiosa atropurpurea	1	0.06	0.17	10	157	10	48	8	A
Medicago arabica	1	0.06	0.06	14	158	10	53	3	E
Lotus corniculatus	1	0.06	0.02	11	158	10	53	1	E
Arctotheca calendula	1	0.06	0.02	23	65	4	42	1	E
Centaurea solstitialis	1	0.06	0.12	15	49	3	95	11	E
Setaria viridis	1	0.06	nd	15	50	3	nd	nd	A
Sporobolus indicus	1	0.06	nd	21	151	9	nd	nd	B
Gastridium phleoides	1	0.06	nd	11	151	9	nd	nd	A
Avena fatua	1	0.06	nd	17	68	4	nd	nd	E
Bassia hyssopifolia	1	0.06	0.13	11	51	3	38	5	E
Cirsium arvense	1	0.06	0.06	14	68	4	31	2	B
Hieracium praealtum	1	0.06	0.06	13	17	1	34	2	A
Sedum acre	1	0.06	0.09	10	69	4	34	3	E
Dipsacus sativus	1	0.06	0.25	15	157	9	48	12	A
Salix babylonica	1	0.06	0.02	12	35	2	48	1	E
Cytisus scoparius	1	0.06	0.11	22	158	9	38	4	E
Briza maxima	1	0.06	nd	19	124	7	nd	nd	E
Atriplex prostrata	1	0.06	0.18	13	124	7	11	2	A
Valerianella locusta	1	0.06	0.07	11	90	5	61	4	A
Trigonella monspeliaca	1	0.06	0.01	12	54	3	68	1	A
Avena sativa	1	0.05	nd	11	73	4	nd	nd	E

Dianthus armeria	1	0.05	0.13	21	37	2	8	1	A
Euphorbia lathyris	1	0.05	0.20	13	187	10	40	8	A
Schismus arabicus	1	0.05	nd	17	78	4	nd	nd	E
Cynara cardunculus	1	0.05	0.14	15	157	8	42	6	E
Vulpia muralis	1	0.05	nd	16	151	7	nd	nd	E
Rumex pulcher	1	0.05	0.24	12	130	6	38	9	A
Eragrostis curvula	1	0.05	nd	14	44	2	nd	nd	E
Cenchrus echinatus	1	0.05	nd	11	88	4	nd	nd	A
Atriplex rosea	1	0.05	0.39	10	22	1	23	9	E
Oryza sativa	1	0.04	nd	10	72	3	nd	nd	A
Chamomilla recutita	1	0.04	0.24	11	124	5	42	10	A
Cymbalaria muralis	1	0.04	0.18	14	124	5	40	7	B
Catabrosa aquatica	1	0.04	nd	13	25	1	nd	nd	E
Hainardia cylindrica	1	0.04	nd	10	50	2	nd	nd	E
Lolium temulentum	1	0.04	nd	17	151	6	nd	nd	A
Sisymbrium altissimum	1	0.04	0.35	18	52	2	23	8	E
Mentha x piperita	1	0.04	0.12	23	156	6	66	8	A
Artemisia absinthium	1	0.04	0.14	18	157	6	42	6	B
Leymus arenarius	1	0.04	nd	12	53	2	nd	nd	A
Geranium dissectum	1	0.04	0.10	13	159	6	39	4	A
Chenopodium vulvaria	1	0.04	0.03	13	80	3	30	1	A
Ammi majus	1	0.03	0.12	10	29	1	78	9	A
Pastinaca sativa	1	0.03	0.41	23	124	4	17	7	E

Chenopodium glaucum	1	0.03	0.14	12	31	1	22	3	A
Helianthus tuberosus	1	0.03	0.04	12	157	5	76	3	A
Medicago polymorpha	1	0.03	0.58	16	158	5	38	22	A
Calendula arvensis	1	0.03	0.03	15	95	3	95	3	A
Diplotaxis muralis	1	0.03	0.38	10	68	2	21	8	A
Tribulus terrestris	1	0.03	0.22	10	114	3	65	14	A
Brassica nigra	1	0.03	0.33	13	159	4	21	7	A
Linum usitatissimum	1	0.03	0.13	21	159	4	40	5	A
Phalaris minor	1	0.03	nd	14	80	2	nd	nd	A
Bromus sterilis	1	0.02	nd	10	81	2	nd	nd	B
Bromus madritensis	1	0.02	nd	12	130	3	nd	nd	E
Stellaria pallida	1	0.02	0.18	11	45	1	22	4	E
Avena sterilis	1	0.02	nd	11	47	1	nd	nd	E
Vulpia myuros	1	0.02	nd	16	151	3	nd	nd	E
Bromus secalinus	1	0.02	nd	13	101	2	nd	nd	A
Atriplex tatarica	1	0.02	0.22	10	51	1	23	5	A
Rorippa nasturtium-aquaticum	1	0.02	0.90	20	159	3	20	18	E
Apium nodiflorum	1	0.02	0.03	10	106	2	78	2	B
Bromus racemosus	1	0.02	nd	10	58	1	nd	nd	E
Atriplex hortensis	1	0.02	0.26	10	121	2	23	6	E
Mercurialis annua	1	0.01	0.08	10	74	1	40	3	A
Asclepias curassavica	1	0.01	0.18	13	75	1	61	11	A
Avena strigosa	1	0.01	nd	17	78	1	nd	nd	A

Calendula officinalis	1	0.01	0.02	11	157	2	95	2	E
Aphanes arvensis	1	0.01	0.05	10	158	2	21	1	A
Erodium malacoides	1	0.01	0.15	21	159	2	39	6	A
Descurainia sophia	1	0.01	0.14	14	159	2	21	3	A
Crepis setosa	1	0.01	0.10	11	84	1	42	4	A
Amaranthus albus	1	0.01	0.08	11	118	1	40	3	E
Sonchus arvensis	1	0.01	0.03	22	157	1	38	1	A
Melilotus officinalis	1	nd	0.29	20	nd	nd	21	6	E