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Foreword

I have spent a good portion of my life studying invasive plant biology and ecology with the goal of developing effective management strategies and programs. Though most of my work has been in North America, I have had the good fortune to travel the world to see the ecological responses and impacts of invasive plants under a variety of climatic and environmental conditions. In one of my international trips to southern China with Dr. David Clements (primary editor of this book) and Dr. Leslie Weston (chapter author), we observed the devastating effects of the invasive mile-a-minute weed (*Mikania micrantha*) on a wide variety of crops and the extensive invasion of southern China forests by Crofton weed *Ageratina adenophora* (or *Eupatorium adenophorum*). My visit to China and other areas of the world demonstrated to me the importance of a global understanding of the ecology and impacts of invasive plants to better prevent, understand, manage, and develop appropriate policies to reduce their environmental and economic effects.

This book provides the most comprehensive global perspective on invasive plants ever published. Its coordination by the editors is a monumental effort, considering the number of authors and their wide range of languages and regions in the world. The task, however, was well worth the effort as the book gives a perspective of invasive plants from nearly every continent on the globe, apart from Antarctica. The authors represent many of the leading invasive plant experts and authorities from 23 countries of North, South, and Central America, Europe, Asia, Africa, and Australia. The book is primarily organized by large land areas or continents but has special chapters on the uniqueness of island and mountain plant invasions, as well as invasion processes, history of global spread, climate change, impacts, advances in management, global strategies, and thoughts on the future. The chapters on global regions provide exceptional coverage of pathways of introduction; distributions with respect to countries or climatic zones; plant traits and life histories that increase invasion success; impacts, both economic and environmental; and policies and legislation important to each region. Having a fascination with history, I found the historical perspective of invasive plant introductions in a variety of continents and countries particularly interesting. These should provide valuable insights on future introductions and spread.

The authors give an outstanding global perspective of invasive plants from each region, which is critical to understanding invasive plants even at a local level. For example, *Ulex europaeus* is native to cooler maritime regions in the western coastal areas of continental Europe and the British Isles. It has become invasive in many regions of the world in a similar habitat, including the California coast, South and Central America, and Australia and New Zealand. Most interesting, it is also invasive in a climatic band on the mountain of Mauna Kea in Hawaii. This band shares a similar climate to its native range. By understanding the global distribution of this and other species, it is far easier to predict susceptible environments. This is also true for predicting environments where a species may not be invasive. In California, *Lantana camara* is a widely planted garden ornamental throughout the state, and *Melaleuca quinquenervia* is a common street tree in the southern region of the state. Both species are not problematic in California, yet this book describes their invasion into many other regions of the world or even within other areas of the United States as bearing more harmful consequences. The similarity in the climatic zones where these species have invaded provides insight as to why the drier Mediterranean climate of California restricts their ability to establish. Again, a global perspective becomes critical to predicting the potential invasiveness of a species in other regions of the world, and this book provides that global perspective.

To make better informed decisions on how to prevent potentially harmful introductions, what plants to prioritize, what climatic or environmental characteristics may contribute to the spread and success of invasive plants, and what local, regional, and global policies or legislation are necessary to mitigate against their impacts, I firmly believe it is critical to understand plant invasions on a global level. From my own limited firsthand experiences studying invasive plants outside the United States, I greatly expand my appreciation for the larger picture regarding individual invasive plant species and threatened ecosystems. After reading through the various chapters of this book, I was so impressed by the tremendous amount of valuable information from so many regions of the world. I could not help but wish that such a volume had been available when I was a student or even during my career as a faculty member. This would have been among my most valuable references on invasive plants, and I believe it will be an important book in the personal library of many others.

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March 30, 2021

Preface

When Charles Elton published his ground-breaking book *The Ecology of Invasions by Animals and Plants* in 1958, he raised the alarm that "A hundred years of faster and bigger transport has kept up and intensified this bombardment of every country by foreign species, brought accidentally or on purpose, by vessel and by air and overland from places that used to be isolated." Although Elton's book essentially marked the beginning of the modern field of invasion biology, it took decades for the fledgling discipline to be taken seriously. Even today, there is a movement within academia labelled "invasive species denialism," arguing that invasion biologists and practitioners tend to exaggerate the harms caused by these species. Meanwhile, regardless of their impacts, these invasions continue at a staggering rate and are truly worldwide in scope as documented in the chapters of this present volume, highlighting global plant invasions.

Given the intrinsic variation in species biology, it is clear that different plant species will vary greatly in their ability to damage and invade various ecosystems, such as natural ecosystems, agroecosystems, or urban environments. Thus, there is a need to carefully assess the impacts of invasive species, avoiding exaggeration but at the same time providing important information on impacts, as detailed in this volume. Even since 1958, much has changed in our relationship with invasive species as globalization and dramatically increased economic growth in certain regions have made the intentional and unintentional transport of invasive species more rampant. Moreover, the specter of global climate change has exacerbated invasion potential, as we have witnessed an accelerated increase in global mean temperature along with other climatic factors that promote the spread of these species. Intrinsically, these species are well-adapted to ride on human coattails and follow us around the globe and thrive where we generate available niches for them. However, this comes at a cost to many sensitive natural ecosystems comprised of plant and animal communities as products of thousands or millions of years of coevolution. Many species have gone extinct as a result of invasive species, and many of these plants have altered ecosystem functions and reduced the value of ecosystem services. Ecosystem services are sometimes difficult to quantify or visualize, but to add to these compromised ecosystem services, there are considerable quantifiable economic costs of invasive species to agriculture, forestry, recreation, urban property values, and other sectors, even impacting iconic cultural landmarks. A full accounting of these costs also includes the exorbitant expenses in managing these invasive pests year in, year out, as they grow and spread "like weeds."

This book volume represents a comprehensive overview of global plant invasions in the early twenty-first century. The first few chapters provide an introduction to the nature of plant invasions, defining their scope and impacts, the dynamics of invaded plant communities, global invasion pathways, and the role of global climate change in fostering further plant invasions. From there, experts from every continent and world region highlight the state of invasion in their areas, with chapters covering plant invasions in Asia, Australia, Europe, North America, South America, Central America, Africa, island regions, and mountainous regions. The subsequent three chapters turn to how to respond to the challenge of global plant invasions, examining biotic and economic impacts, advances in management, and the design of global strategies for managing invasive species. In the final chapter, well-known invasion biologist, Daniel Simberloff, addresses the question of whether we are heading to a "future planet of weeds" and what this means for the well-being of our planet and ourselves.

The subject of global plant invasions is very broad and complex, with every world region facing specific issues around particular invasive species. Yet many of the issues are common to many geographic regions, and many invasive plant species have spread via human agency across multiple continents – including lantana, knotweed species, gorse, mile-a-minute weed, water hyacinth, parthenium, prickly pear, ragweed, giant reed, cordgrasses, Siam weed, Himalayan balsam, and mesquite. Thus, there is value in having these global portraits of plant invasions collected in a single volume, provided by expert scientists from across the world who have seen firsthand the impacts and challenges posed by these species. This book provides a comprehensive tool in the hands of undergraduate students and graduate students, invasion biologists from academic and government institutions, nongovernment organizations, policy-makers, and numerous other agencies developing strategies and actions to manage invasive plants on local and global levels. The field of invasion biology is still a young seedling, and this book is full of suggestions for further research and development of this emerging field.

We are very grateful to all the authors for their excellent contributions – it has been a privilege to work with each one of them. We also thank the staff at Springer Nature for their kind support, the external reviewers for providing helpful feedback on the chapter manuscripts, and our families for their encouragement and patience through the long but fruitful process of putting this book together.

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Joseph DiTomaso shows how adventitious roots form to help facilitate rapid spreading of mile-a-minute weed (*Mikania micrantha*) in Yunnan Province, China. Photo credit: David Clements

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1 Global Plant Invasions on the Rise

David R. Clements, Mahesh K. Upadhyaya, Srijana Joshi, and Anil Shrestha

Abstract

The data available on the extent of global plant invasion shows a sharp increase in cases and associated costs over the last several decades. Indeed, most of the mixing of the planet's flora due to human agency has occurred in the last 200 years. As in the case of rapidly emerging human pandemics that demand timely action, there have been urgent calls to stem the tide of plant invasions and prevent further spread and associated environmental and socioeconomic impacts. However, the response to most actual and potential plant invasions is far from simple. Naturalized plants have a broad range of impacts, such that a response specific to the particular plant species and habitat is often advisable, along with a meaningful dialog among stakeholders. Given the massive scale in changes of the flora in various regions, many naturalized species with minimal impacts are best left alone, whereas other naturalized species that have massive impacts warrant management to prevent further, often irreversible, effects on ecosystems. There exists a considerable array of invasive plants in this category, most of which are truly global, distributed on multiple continents. Of these high-impact invasive plant species, 37 are on the list of the International Union for Conservation of Nature (IUCN) 100 worst invasive alien species. Most of these high-impact species continue to spread in their non-native ranges, including sensitive island and mountain habitats. They also cause a range of socioeconomic impacts on agriculture, forestry, transportation, infrastructure, and cultural values. If current trends in plant invasions continue and are exacerbated by increasing global trade and climate change, many challenges lie ahead. We cannot turn back the clock to recover natural habitats free of invasive plants in most cases, but there are still ways of promoting ecosystem health through reducing populations of high-impact invasive plants and promoting holistic approaches to planet healing.

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Biosurveillance · Climate change · Globalization · Invasive plant costs · Island invasions · Planet of weeds · Plant invasion

1.1 Introduction

Many global issues are in ascendance at this point in world history, and there can be little doubt that global plant invasions are on the rise with rates exacerbated by many other forces operating at a global scale, such as climate change and ever-expanding world trade (Meyerson and Mooney 2007; Ziska et al. 2019; Hulme 2021a). Diagne et al. (2021) estimated a worldwide mean annual cost of biological invasions of \$26.8 billion USD between 1970 and 2017, which by 2017 had reached \$162.70 billion USD annually, showing a continual increase with no signs of leveling off. These estimates included the costs of damage due to invasive species and their necessary management, with both likely grossly underestimated due to lack of available data. There are challenges associated in accurately estimating such costs, but more broadly, there is a need for more research on invasive species generally, and invasive plant species specifically, in order to better understand their biology and ecology, as well as their environmental and economic impacts (see Chap 14 for a more detailed assessment). Better-informed international strategies and policies can be developed to tackle this global problem (see Chap 16). In the meantime, it is clear that proactive actions are required immediately to prevent the seemingly inevitable progression towards a "planet of weeds" (Quammen 1998; van Kleunen et al. 2015; Pyšek et al. 2017, 2020; Seebens et al. 2018; Chap 17).

Seebens et al. (2017) analyzed the first reports of species invasions over the past 200 years and found that 37% of these were reported between 1970 and 2014, with no signs of slowing down. Many species in more recent invasions had never been observed to be invasive previously, thus the pool of potential invaders is also on the rise (Seebens et al. 2018). Seebens et al. (2021) used a modeling approach to predict establishment of naturalized alien invasive species and estimated that, by 2050, their total number would increase globally by 36%. Thus, we can anticipate continual species invasions for the foreseeable future, despite our efforts to stem the tide through the development of better management and surveillance. The pace of globalization is much greater than the efforts to manage invasive species (Seebens et al. 2017; see also Chaps 2 and 16). At the same time, economic costs associated with the damage and management of invasive species are on the rise (Diagne et al. 2021).

Recent pandemics, most notably the SARS-CoV-2 pandemic that emerged in 2020, serve as a strong wake-up call on the extent of globalization and profound risks associated with it. Invasion biologists have made important connections between invasive species and pandemics caused by human pathogens. Vilà et al. (2021) called global pandemics "quintessential biological invasion events" and argued that there is a strong parallel between epidemiology of pandemic organisms and invasion biology, which investigates how species are moved far from their point of origin to various points on the globe via human agency. In many cases the two fields are more directly related, such as when macroscopic invasive species carry pathogenic organisms, increasing human transmission rates (Vilà et al. 2021). Given the close alignment between the two fields, it makes sense to promote sharing of techniques and approaches between them (Ogden et al. 2019). In fact, Hulme (2021b) strongly advocates for a more unified approach to biosurveillance in general, given the risk of failure of more disjointed approaches, as we have seen with respect to both the SARS-CoV-2 pandemic and global species invasions. A growing body of knowledge on invasive plants is available, but the development of worldwide strategies for managing them is still in its infancy, suffering from sizeable gaps between science, management, and policy at various scales (see Chap 16).

In this chapter we provide an overview of the state of the science of plant invasion biology and opportunities to avoid future invasion of plants.

We begin by presenting a brief history of the science, together with outlining the concepts and definitions in the field of invasion biology. This is followed by a geographic overview, mirroring the book chapters that cover various world regions (Chaps 5, 6, 7, 8, 9, 10, 11, 12 and 13). Next, we address the impacts of invasive plants and the challenges associated with measuring these impacts. Finally, we complete the introduction to the status of this crucial field in our time by giving a brief horizon scan of the way forward, with the rest of the story contained in subsequent chapters by other experts in the field.

1.2 Overview of Invasion Biology with a Focus on Plant Invaders: History, Concepts, and Definitions

1.2.1 Brief History of Invasion Biology

The publication of *The Ecology of Invasions by Animals and Plants* by Charles Elton in 1958 marked a clear beginning of the modern field of invasion biology (Davis 2006). Even in 1958, the pace of change due to globalization was seen as promulgating invasion, as Elton (1958) states: "A hundred years of faster and bigger transport has kept up and intensified this bombardment of every country by foreign species, brought accidentally or on purpose, by vessel and by air and overland from places that used to be isolated." In the book's preface, he stated that his goals included pulling together three streams: faunal history, ecology, and conservation, with the latter tending to be the overriding theme (Davis 2006). The text was also marked by graphic battlefield examples of invasions, likely inspired by post-war reflections on World War II. It is also important to note that there were invasion biologists who preceded Elton, including Swiss Botanist Thellug (1881–1918) whose work provided the basis for many unifying concepts in the field (Kowarik and Pyšek 2012). Despite Elton's contribution in the 1950s, the field of invasion biology had limited uptake by researchers until the 1980s, but from then on, citations in the field of invasion ecology increased steadily, outpacing citations of many other traditional ecological topics (Pyšek et al. 2006). Some of this activity was catalyzed by the work of Richard Mack on plant invasions in western North America, focusing on a conservation theme (Mack 1981; Davis 2006). However, it was not until the 1990s that many more scientists participated in the pursuit of invasion biology research, producing a "flood of publications" that continues to this day (Davis 2006; Richardson and Pyšek 2008; Cassini 2020). By the 1990s, policy makers were beginning to comprehend the magnitude of the issue, and when the United Nations Convention on Biological Diversity (CBD) was created at the 1992 Rio Earth Summit, it included provisions for signatories to control or eradicate invasive species (Lindgren 2012). In February 1999, an executive order was signed by the US President calling for action against invasion of alien biological species in the United States, which also set off alarm bells around the world (Clements and Corapi 2005).

In 2008, 50 years after the publication of Elton's 1958 book, the field of invasion biology had grown considerably, and the book was still the most cited in the field, with 1516 citations by May 2007 (Richardson and Pyšek 2008). Thus, the basic principles set out by Elton have served the discipline well, although the species under consideration and the theoretical underpinnings have radically changed since the book was published (Richardson and Pyšek 2008). As invasive species research and management has continued to grow from 2010 onwards, critiques of the field have also multiplied (Blondel et al. 2014; Van der Wal et al. 2015; Cassini 2020; Davis 2020) along with defenses of the discipline (Richardson and Ricciardi 2013; Rejmánek and Simberloff 2017; Russel and Blackburn 2017; Ricciardi and Ryan 2018). One of the most important concerns regards the very definition of invasive species.

1.2.2 Defining Invasive Plants

Invasive species biology is often criticized for the lack of universal adherence to concepts and principles (Cassini 2020). Because a wide range of plant species may be labeled as "invasive," it is difficult to generalize. Weed scientists tend to refer to invasive plants as "environmental weeds" to distinguish them from agronomic weeds (Sheppard et al. 2006); however, the two categories are clearly not mutually exclusive because many "environmental weeds" also invade agroecosystems, and vice versa (Thomas and Leeson 2007; Clements 2017). Colautti and MacIsaac (2004) located the following definitions in the literature: a non-native species (Goodwin et al. 1999; Radford and Cousens 2000); a native or non-native species that has colonized natural habitats (Burke and Grime 1996); a widespread non-native species (van Clef and Stiles 2001); and a widespread non-native species that has a negative effect on habitat (Davis and Thompson 2000; Mack et al. 2000). Blondel et al. (2014) argued for a broader definition, referring to the Latin term *in-vadere*, arguing this should be the fundamental element in the development of invasion science, regardless of whether such invasions were human-mediated.

Blackburn et al. (2011) developed a unified framework, representing a "single conceptual model that can be applied to all human-mediated invasions" that is widely used by invasion biologists. The framework includes terms to be applied to species at different invasion stages. "Alien species" are species transported to areas where they are non-native through human agency. Alien species are classed as "casual/introduced" if they are not reproducing in the new environment, referred to as "naturalized/established" if they are able to reproduce, and "invasive" once they demonstrate the ability to spread in the new environment (Blackburn et al. 2011). The division among the three terms "introduced," "naturalized," and "invasive" is important, recognizing that many introduced species never become naturalized, and of these relatively few become invasive (Richardson et al. 2000). The difference between the self-sustaining naturalized populations and invasive populations is somewhat subjective but essentially requires that a species has demonstrated the ability to disperse beyond the site of introduction (Richardson et al. 2000; Blackburn et al. 2011). Legal definitions of invasive species have been developed to support their management by governmental and nongovernmental agencies. The legal definition employed in the 1999 US Executive Order was "an alien (or non-native) species whose introduction does or is likely to cause economic or environmental harm or harm to human health" (Executive Order 13112, 1999). The International Union for Conservation of Nature (IUCN) defined an alien invasive species as a species "which becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity (IUCN 2000).

When a particular invasive species is highlighted, the big question is often "what impact does it have?" However, impact may be difficult to define precisely. Jeschke et al. (2014) developed seven questions to attempt to unpack invasive species impact:

1. Are only unidirectional changes considered or are bidirectional changes considered?
2. Is the definition as neutral as possible or are human values explicitly included?
3. Is the term *impact* only used if the change caused by a non-native species exceed a certain threshold, or is it used for any change?
4. Are ecological or socioeconomic changes considered, or both?
5. Which spatio-temporal scale is considered?
6. Which taxonomic or functional groups and levels of organization are considered?
7. Consideration of per capita change, population density, and range?

These questions illustrate some of the dilemmas faced by scientists in characterizing invasive species. For example, question 1 demonstrates that some impacts of invasive species on an ecosystem may actually be positive, or both negative and positive. Likewise, question 3 shows that impacts may cover a broad range, and from a management point of view, it may be challenging to choose at what point should action be taken, especially if the threshold is not clear. The remainder of this chapter, and indeed the rest of the book, provides further input on these important questions.

1.2.3 The Plant Invasion Process

Invasion scientists commonly refer to a typical invasion history consisting of three fairly distinct phases: (1) a lag phase after the initial invasion when the invader is relatively uncommon and found in isolated locations, (2) an exponential growth phase when the species rapidly increases both in population size and distribution, and finally (3) a period of time up to the present when the population and distribution have reached their maximum extent, subject to occasional fluctuations due to variation in conditions, including attempts to manage the invasive species (Fig. 1.1). These three phases have also been characterized as introduction, colonization, and naturalization phases (Radosevich et al. 2003). During the lag phase, the invasive species may be difficult to detect and often seen as posing limited risk because of its low abundance. The lag phases of invasions have been documented to range from a few years to centuries in length (Pyšek and Prach 1993; Crooks 2005; Larkin 2012). It is likely that a variety of mechanisms account for the lag phase including dispersal limitations, availability of empty niches, and genetic or phenotypic changes in the invaded range (Clements and DiTommaso 2011; Espeland 2013; Perkins et al. 2013; Murren et al. 2014). Of course, not all invasions follow the typical trend, and many invasions are not nearly as successful. According to Williamson's (1996) "Tens Rule," only 10% of species entering a dispersal pathway disperse, 10% of these establish in the adventive habitat, and among the species establishing, only 10% become problematic, i.e., the invasive species that follow the pattern in Fig. 1.1.

Several studies have analyzed invasion history in an attempt to predict invasion patterns better, through examining herbarium records and various other forensic ecology methods. Larkin (2012) failed to detect an overriding explanation predicting length of the lag period among several species with periods ranging from 3 to 140 years. Similarly, Flores-Moreno et al. (2015) followed the fate of three invasive plants in the United Kingdom over 200 years and found that these species did not require time to evolve responses to the habitat. By contrast, Fennell et al. (2014) found greater genetic variability in seeds of giant rhubarb (*Gunnera tinctoria*) in Ireland before populations transitioned to the exponential phase. For introduced rangeland plants in the western United States established for periods between 41 and 86 years, Morris et al. (2013) found that while some species followed the usual logistic invasion curve, others showed sporadic crashes and spikes in abundance, likely due to periodic droughts in this relatively arid environment.

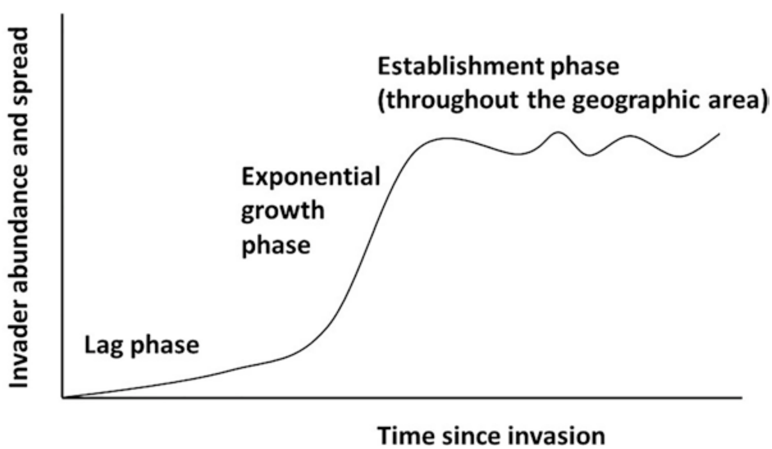

Fig. 1.1 Commonly observed trend in the abundance of non-native species invasions over time, illustrating three major phases often recognized in the invasion process

Mosena et al. (2018) computed invasion curves for ten invasive plants in western North America and observed some were logistic while others were more linear. They also computed proportional changes in counties occupied, which allowed them to gain more insight into the geographic spread. For example, the major range expansion period for cheatgrass (*Bromus tectorum*) extended from 1900 to 1950, well beyond the 1900–1930 expansion period emphasized by Mack (1981). Examining the invasion history of 155 tropical grasses invading Australia, van Klinken et al. (2015) showed how 21 of these became widespread and problematic but predicted few new invasions by grass species will occur in Australia.

A key question behind attempts to characterize invasion curves and their history is whether potentially serious invasive species can be detected and dealt with early in the invasion sequence. The potential for eradicating and the cost of eradication is far more favorable in early invasion stages, but it is difficult to predict the seriousness of an invasion early (Daehler 2003; Larkin 2012). In order to attempt to catch potentially serious invaders early in the curve, government agencies and others charged with managing invasive species frequently employ (1) early detection and rapid response (EDRR) and (2) weed risk assessment (WRA).

EDRR advocates argue that from the precautionary principle, virtually all recent or potential invasive species should be assumed to be a serious threat (Westbrooks 2004; Crooks 2005). Given the modest amount of funding available for invasive weed control in California, Funk et al. (2014) pointed out the massive savings from controlling species as early as possible post invasion, and this is all the more true for many other areas around the world where funding is even scarcer. However, because there are so many potential invaders, WRA is a useful tool for prioritizing which invaders are likely to cause the greatest harm. WRA models make use of expert knowledge on potential invasive species, including a variety of measures related to the potential for spread or impact in other geographic areas (Pheloung et al. 1999). However, Hulme (2012) pointed out that risk assessments are inherently flawed due to the subjectivity of experts and high levels of uncertainty predicting plant invasion dynamics. McGregor et al. (2012) found that the Australian WRA predicted naturalization well but failed to consistently predict the extent of spread. Hulme (2012) recommended augmenting the WRA approach using knowledge of experts to assess uncertainties accompanying weed population and human management dynamics (e.g., interventions to improve ecosystem resilience). More sophisticated approaches to risk assessment are currently under development, e.g., an approach that combines information from knowledge of the invasive plant species and potential recipient ecosystems, utilizing the growing body of knowledge available on both aspects (Probert et al. 2020a). Furthermore, many new invasive species are now emerging, and WRA methods that rely on historical knowledge may no longer be relevant because experts are unaware of risks posed by these new invasive species (Seebens et al. 2018). One useful approach is to look at risks associated with particular taxonomic or functional groups, rather than trying to assess risk across all plant groups. Frameworks have been developed to assess risks associated with various plant groups, such as bamboos (Canavan et al. 2017), Cactaceae (Novoa et al. 2015), and conifers (Richardson and Rejmánek 2004).

Because of the nature of the lag period, managers often fail to realize the high costs of invasions until it is too late (Westbrooks 2004; Mack et al. 2000). A critical question is whether or not impacts can be predicted in advance. Van Klinken et al. (2013, 2015) studied 155 tropical and subtropical grasses in Australia to determine if effects on natural environments, pastures, or agricultural crops could be predicted. Among 155 tropical and subtropical grasses invading Australia, the best predictors of costs were how fast they spread and whether they were semi-aquatic (van Klinken et al. 2013, 2015). The most important invasion pathway for these grasses was through intentional introduction of pasture species to Australia (Van Klinken et al. 2015), a pathway that has contributed to colonization by grass species the world over (Mack et al. 2000;

Morris et al. 2013). Similarly, horticultural introductions, which by definition are intentional, feature prominently among invasion pathways (Reichard and White 2001; Lambdon et al. 2008; Hulme 2009; Barbier et al. 2011). To this day, such pathways are prominent sources of invasion, and increased globalization and commerce tend to exacerbate such invasions.

The study of plant invasion pathways poses the question: How did each of the more than 13,000 naturalized plants throughout the world (Pyšek et al. 2017) arrive at their destinations? Although over the past 500 years many different pathways have been identified, the pathway responsible for more than half of all plant invasions has been deliberate introduction of plants for horticulture and other forms of cultivation (Chap 3). More broadly speaking, the three most important pathways have been introductions for food production, ornamental purposes, and accidental releases (Saul et al. 2017; Pergl et al. 2020). We have witnessed three major waves of plant invasion (di Castri 1989): the age of exploration (1500–1800), the age of industrialization (1800–1950), and the age of globalization (1950 to the present), with each succeeding wave greater than the previous one.

1.2.4 Recent Trends and Drivers of Plant Invasion Including Globalization, Increased Trade, and Climate Change

Many attempts have been made to describe the major drivers of plant invasion. It is tempting to ascribe most of the agency to the invasive plants themselves, because they indeed possess many remarkable qualities, and most invasive plant researchers have a great deal of respect for their subjects, even if the ultimate aim of the research is to control or eradicate these species. However, it is clear that in many cases, the invasive plants should be seen more as the passengers rather than the drivers of the invasion process (MacDougall and Turkington 2005). In the Garry oak ecosystem studied by MacDougall and Turkington (2005), the invasive grasses benefitted from an ecosystem already being degraded, through a disturbance regime highly modified from its historical baseline state. Thus, reduced ecosystem resistance was the major factor precipitating change. In other settings, invader fitness could be the major driver, or in still other situations climate dynamics could be key. Young et al. (2017) developed a framework for looking at these three factors: ecosystem resistance, invader fitness, and climate dynamics simultaneously, in order to examine the forces determining how well invasive plants invade communities (see also Chap 2).

Each of the elements in the framework devised by Young et al. (2017) involves a considerable array of dynamic factors, and thus understanding plant invasions, and attempting to develop a better system of predicting them, requires an in-depth examination of all three elements. Although there are numerous studies of the three factors in isolation, there is a need for integrated research involving all three elements of the framework (Young et al. 2017; Chap 2). It is relatively easy to produce a map which predicts areas that are climatically suitable for a particular plant invader, but unless ecosystem resistance is overcome (e.g., via anthropogenic disturbance), the plant will not invade a particular area. By the same token, models that predict expanding ranges of invasive plants under climate change may underestimate the extent of invasion for invasive species that evolve in response to changing conditions along the invasion edge, thus increasing invader fitness (Clements and DiTommaso 2011). Indeed, numerous recent studies are revealing that invasive plants can evolve relatively rapidly to changing climatic conditions and that this ability represents a major challenge to their management (Ziska et al. 2019; Clements and Jones 2021a, b).

Humanity ignores the critical linkage between invasive species and climate change at its peril (Seebens et al. 2015; Ziska et al. 2019; Chap 4). It is important to recognize the particular impact of climate change on invasive plants due to the interaction between CO_2 levels and photosynthesis, whereby increased CO_2 impacts plants both through potential increases in photosynthesis and global warming (Ziska et al. 2019). It is also important to understand that many other features of climate change interact with invasive plants, such as more frequent flooding, droughts, storms, fires, and other extreme events (Colleran and Goodall 2015; Wu and Ding 2019; Fraterrigo and Rembelski 2021; Chap 4). Climate changes not only promote greater spread of plant invasions but also reduce our ability to manage them, through reduced efficacy of herbicides and other methods (Ziska 2020; Clements and Jones 2021a), thereby increasing the costs of management (Rhodes and McCarl 2020).

Globalization and increasing world trade are unquestionably driving much of the rise in plant invasions, with global trade synonymous with the movement of invasive species hitchhiking on commerce, or even the subject of commerce in many cases, e.g., the horticultural trade (Hulme 2021b). Effects of globalization on plant invasions have been well documented, particularly for countries like China where the recent increase in economic growth and trade has resulted in widespread introduction and proliferation of invasive plants (Ding et al. 2008; van Kleunen et al. 2015; Horvitz et al. 2017). Direct effects of globalization on the rate of plant introductions via horticultural trade are well supported by the research (Taylor and Irwin 2004; Pyšek et al. 2010; van Kleunen et al. 2018; Guo et al. 2019). Indirect effects of globalization on invasive species issues are more challenging to understand and quantify. The full scope of indirect effects includes the way that growing trade transforms economies, making nations more likely to import invasive species or to create an environment conducive to invasion. Hulme (2021b) argues that these indirect effects have a far greater impact than direct effects. One striking indicator of the overall trend since the nineteenth century is how the increasing percentage of imports of the global GDP closely mirrors the increasing frequency of number of first records of alien species (Hulme 2021b). Furthermore, the relationship between international trade and invasive species is a rapidly moving target, due to labile trading relationships between countries, supply chain disruptions, newly emerging modes of trade (e.g., e-commerce), and, as recently highlighted, pandemic influences (Epanchin-Niell et al. 2021). Given how much the rise in the numbers of new invasions is tied to globalization, Meyerson and Mooney (2007) argue for a concomitant globalization of the knowledge of invasive species to help better coordinate international efforts to deal with invasive species.

1.3 The Geography of Plant Invasions

By definition, plant invasions consist of changes in geographic distribution. Earlier research on plant invasion biology focused mostly on Europe and North America. There was also an earlier focus on island ecosystems, as being clearly very vulnerable to invasions (see Chap 12). Increasingly, however, many invasive plants have become more global, with many species distributions now spanning several continents, highlighting the need for a coordinated global approach to their management (Hulme 2021b; Chap16). There are 11 invasive plants present in at least 35% of world regions within their invaded range, with the most widely distributed species being common sowthistle (*Sonchus oleraceus*) (Pyšek et al. 2017). In terms of invasive ranking within regions, lantana (*Lantana camara*) is at the top of the list, occurring in 120 out of 349 regions with data on invasive status (Pyšek et al. 2017), with 4 other species [apple of Sodom (*Calotropis procera*), common water hyacinth (*Eichhornia crassipes*), common sowthistle, and leucaena (*Leucaena leucocephala*)] having invasive status in over 100 regions (Pyšek et al. 2017).

1.3.1 The Invasion State of the World's Continents

Prior to intercontinental introductions of plants by humans, particularly before the first major invasion wave in the age of exploration beginning in 1500, the flora of each continent was relatively unique, producing co-evolved plant communities specific to various natural ecosystems. Agroecosystems have featured a more universal flora, dating back to times when crop species were subject to long-distance introductions. Crops were moved along with a complement of agricultural weeds, many of which are among the most widespread organisms on earth (Harlan and de Wet 1965; Krähmer 2016). The more recent invasion by non-native plants on a global scale has gone far beyond agriculture. These introductions include some serious agronomic weeds as well as numerous plants that impact natural areas, urban habitats, recreation, and even cultural monuments in their invasive ranges. Many of these invasive plants [e.g., common ragweed (*Ambrosia artemisiifolia*) and mile-a-minute (*Mikania micrantha*)] affect both agricultural and non-agricultural environments (Bassett and Crompton 1975; Day et al. 2016).

Asia, the world's largest continent occupying 30% of the world's surface, represents a broad target for invading plants. In recent decades, increase in trade by orders of magnitude has provided many opportunities for invasive plants to reach Asian countries and flourish (Chap 5). Increases in global trade have brought numerous tropical or subtropical invasive plants, often originating in Latin America, including many notorious invaders such as Crofton weed (*Ageratina adenophora*), Siam weed (*Chromolaena odorata*), lantana, leucaena, mile-a-minute, giant sensitive plant (*Mimosa diplotricha*), parthenium weed (*Parthenium hysterophorus*), and common water hyacinth (*Eichhornia crassipes*). Many of these invasive plants are problematic in other tropical or subtropical areas, such as Australia, Africa, or the Pacific Islands. Common water hyacinth is native to South America and found in all the continents except Antarctica, infesting waterways, disrupting human activities, and denigrating ecosystem services (Coetzee et al. 2017). Although hundreds of non-native vascular plant species are listed as naturalized in Asia, the numbers are relatively low compared to Western Europe and North America (van Kleunen et al. 2015). For many Asian countries, very little data is available on naturalized species. Given human population growth and growth of commerce in Asia, numbers of naturalized species are bound to increase (Seebens et al. 2015; Chap 5). Because Asian countries vary greatly in their ability to track and manage invasive species, there is an urgent need for better coordination of efforts across the continent (Clements et al. 2019; Chap 5).

In contrast to Asia, Australia ranks as the world's smallest continent. Its invasion history is also very different from the other continents because Europeans only arrived and began introducing non-native species 230 years ago (Chap 6). These introductions have had profound effects on the very unique flora and fauna that were products of millions of years of evolution over the time when Australia was isolated from other land masses. By 2017, nearly 30,000 alien plant species had been introduced to Australia, of which 3027 were reported as naturalized (Randall 2017; Chap 6). This tidal wave of invasive plants over the past several hundred years have had a substantial impact on the native flora and fauna, with particular invasive plants such as cactuses (not native to Australia) having become "textbook examples" of plant invasions. Prickly pear (*Opuntia inermis* and *O. stricta*) infestation reached 24 M hectares at its peak in Australia, with densities reaching 16,000 plants per hectare and seriously impeding livestock production (Dodd 1940). Mass releases of the cactoblastis moth (*Cactoblastis cactorum*) native to South America in 1926 were eventually successful in their management (Dodd 1940). Many cactus species however still impact habitats throughout the continent to this day (Novoa et al. 2015). Reflecting Australia's status as a developed nation, considerable resources have been deployed to manage invasive plants, often utilizing the best available technology (Chap 6). Australia thus provides many useful examples to the rest of the world, often in devising ways to manage some of the world's worst invasive plants [e.g., lantana, kochia (*Bassia scoparia*), Paterson's curse (*Echium plantagineum*), and many others], including innovative biosecurity measures to prevent importation of plant species that are likely to be highly invasive.

Although, formerly, Europe was thought of as more of a source than a receiver of invasive plants, particularly since the majority of invasive plants in North America originated in Europe (see Chap 8), it has recently become clear that Europe is impacted by a considerable array of invasive plants (Chytrý et al. 2008; Pyšek and Hulme 2011; Rumlerová et al. 2016; Nentwig et al. 2018; Chap 7). Seebens et al. (2021) have predicted that Europe would see the most new naturalized alien invasive species among the continents by 2050. Via the Global Naturalized Alien Flora (GloNAF) database (van Kleunen et al. 2019), Pyšek et al. (Chap 7) showed that of the 4139 naturalized species, the majority originated from other parts of Europe and there are 1926 species that arrived from other continents, mostly temperate Asia. Invasive plants introduced from North America are causing the same kinds of negative impacts over a broad range of habitats, as has been seen in European introductions to North America. The four top-ranking invasive species with the greatest potential impacts in Europe were silver wattle (*Acacia dealbata*), lantana, kudzu (*Pueraria lobata*), and common water hyacinth (*Eichhornia crassipes*) as ranked by Pyšek et al. (Chap 7). These species also have also serious impacts elsewhere in the world.

Among all the continents, North America boasts the highest number of naturalized plants, a whopping 5958 species (van Kleunen et al. 2015; Pyšek et al. 2017; Seebens et al. 2021; Chap 8). Although these species have been arriving for centuries since the time of European colonization, a rapid increase in plant invasion through various pathways such as horticulture, the aquarium trade, and agricultural contamination has occurred in the past 35 years. Within North America, levels of naturalization vary. California, one of the most invaded world floras with 1753 invasive plant species, has the dubious distinction of being "the world's richest region in terms of naturalized alien vascular plants" (Pyšek et al. 2017). By contrast, Arctic regions in Canada exhibit relatively low levels of plant invasions. As seen in the world at large, the abundance and diversity of invasive plants areas are often linked to higher economic activity. Climate also plays a significant role in this regard. The North American continent features a variety of climate types, some of which are more favorable to plant invasion. Despite relatively intense efforts to manage invasive plants, there are many significant invasive plants in North America [e.g., knotweeds (*Reynoutria* spp.), kudzu, yellow starthistle (*Centaurea solstitialis*), cheatgrass (*Bromus tectorum*), ventenata (*Ventenata dubia*), wild oat (*Avena fatua*), and kochia)] that are still increasing in terms of distribution and/or abundance and may increase further with climate change (Clements et al. 2016; Smith et al. 2018; Becerra et al. 2020; Chen et al. 2020; Harron et al. 2020; Harvey et al. 2020).

There are 9905 naturalized vascular plant species recorded in the New World compared to 7923 species in the Old World (Pyšek et al. 2017). South America has at least 2677 known naturalized non-native plants (van Kleunen et al. 2015; Pyšek et al. 2019; Chap 9). It also exhibits high levels of biodiversity, including the highest number of plant species compared to all other continents, and international biodiversity hot spots such as the Amazon rainforest that may be very sensitive to the impacts of plant invasions. Although from the limited research on the extent of invasive species and their relationship to the diverse various habitats in the continent it is clear that invasive species may have serious effects on South American ecosystems, more work is needed to better understand the extent of these effects (Chacón et al. 2009; Herrera and Nassar 2009; Jäger et al. 2013; Zenni 2015; Valduga et al. 2016; Sandoya et al. 2017; Dechoum et al. 2018; Gantchoff et al. 2018; Baruch et al. 2019; Heringer et al. 2019; Chap 9). Central America has fewer known naturalized plant species than South America; yet the total estimated at 1628 non-native plant taxa is substantial (Chap 10). The diversity of regions within Central America is evident in that only 3.9% of the invasive plant species are common to all Central American countries. As with South America, while there are some studies quantifying naturalized invaders in various Central American countries, more research is needed to better understand their impacts (Christenhusz and Toivonen 2008; Chacón-Madrigal 2009; Lopez 2012; Bonnett et al. 2014; Daniel and Rodríguez 2016; Chap 10). European colonizers brought non-native plant species both as crops and hitchhikers to Central America. This along with habitat modifications (e.g., the transformation of landscapes by cash crops) has made some of the most biodiverse habitats on earth vulnerable to invasive species which have continued to arrive in recent decades due to trade and globalization.

Africa, the second largest continent in both area and population, attracts its fair share of plant invasions, with 1139 naturalized plant species in South Africa alone. Other African countries, however, have considerably fewer recorded invasions (e.g., 50 or fewer naturalized plant species for Djibouti, Gambia, Malawi, and Niger (Pyšek et al. 2017; van Kleunen et al. 2019; Chap 11). As with other less technologically developed regions, the non-naturalized flora is not very well studied in poorer African countries. As a result, the number of naturalized species is likely to be underestimated for these countries, and there is a need for more systematic surveys. South Africa, which also has a greater number of problematic invaders, is the only African country that has consistently delivered systematic and well-funded approaches to invasive species management (van Wilgen et al. 2020). Among the numerous naturalized plants in Africa, there are at least 20 naturalized plant species that clearly earn the title as "transformer species" (Richardson et al. 2000), transforming natural vegetation over a considerable swath of Africa (Chap 11). While many of these transformers [e.g., such as lantana (*Lantana camara*), common water hyacinth (*Eichhornia crassipes*), prickly pear (*Opuntia stricta*), giant sensitive plant (*Mimosa pigra*), leucaena (*Leucaena leucocephala*), and parthenium weed (*Parthenium hysterophorus*)] have already been mentioned to be present in other continents, some species are more uniquely an issue for African ecosystems (e.g., several species of *Acacia* from Australia). With so many species that have transformative impacts on African ecosystems, the potential for the spread of new species, and varying abilities of countries in the continent to deal with these plant invasions, a more coordinated approach is necessary. Because the livelihoods of so many in the continent directly depend on the land, invasive species can have devastating impacts on communities. For example, Pratt et al. (2017) demonstrated that annual costs associated with parthenium weed amounted to $50-80 million US dollars for African smallholders producing maize in Ethiopia, Kenya, Tanzania, and Uganda.

1.3.2 Are some Areas Particularly Vulnerable to Invasions?

As mentioned with respect to continents like South America, biodiversity hot spots are of great concern with respect to ecological impacts of invasive species. Areas with unique habitats and high levels of endemism such as Oceanic islands (Chap 12) or mountains (Chap 13) tend to be highly vulnerable to invasions. In addition to mountains, there are other terrestrial habitat "islands" which may contain unique and vulnerable flora and fauna, such as freshwater habitats (Dextrase and Mandrak 2006; Kiruba-Sankar et al. 2018; Bolpagni 2021).

The relatively small percentage of the Earth's total land area occupied by oceanic islands (less than 5%) belies their contribution to global plant diversity, comprising more than 25% of the world's plant diversity and home to numerous endemic plants. For example, the Hawaiian native vascular plant flora is more than 90% endemic, comprised largely of plant species found nowhere else in the world (Sakai et al. 2002). At the same time, the precipitous decline in these Hawaiian endemic plants, with many documented extinctions, has been clearly linked to overwhelming numbers of invasive animals and plants since Captain Cook "discovered" the islands in 1778. Thus, the Hawaiian and the numerous other remote islands represent a serious conservation crisis, with a race against time to prevent further erosion of the native species populations and diversity by managing invasive species and other factors contributing to decline such as habitat loss (Chap 12). Because such islands are so remote, the ocean generally represents a relatively impenetrable barrier to invasion, but tourism and other forms of development have broken down this barrier in many cases (e.g., Hawai'i, Fiji, Caribbean Islands, and other popular tourist destinations). Thus, the normally very slow rate of arrival of new species to islands and associated gradual evolution of island flora and fauna over long expanses of time has been disrupted by extremely rapid transport of new species in the modern age (Sax and Gaines 2008; van Kleunen et al. 2015; Dawson et al. 2017; Pyšek et al. 2017; Chap 12).

It is not only the rate of change that is of concern but also the types of plants that are becoming naturalized on islands, creating a very different flora with a completely different array of plant traits. Island floras are generally disharmonic by comparison to mainland floras, meaning they contain a unique complement of plants with certain traits or are limited with respect to taxonomic groupings. Naturalized plants, by contrast, will reflect more on the purposes for which the plants were brought by humans (Hulme et al. 2008; Weigelt et al. 2015) and ultimately come to represent more the world's phylogenetic plant species composition than the unique island species profile (Chap 12). More often though it is largely a single (or relatively few) invasive plant species that overruns island habitats. Ceylon raspberry (*Rubus niveus*) has infested 100 of the 585 km^2 comprising the island of Santiago in the Galapagos (Renteria et al. 2012). The price tag for eliminating it is about $10 million USD. Miconia (*Miconia calvescens*) overran large areas of Tahiti (Meyer and Florence 1996) and similarly threatens large areas of the Hawaiian Islands, with costs for control amounting to millions of dollars over the past several decades (Burnett et al. 2007; Leary et al. 2014). Still the isolation of oceanic islands presents unique opportunities to develop sophisticated biosecurity systems to prevent further invasions. In many ways, island biosecurity and management efforts have provided the best examples for the world to follow. Island systems such as the Hawaiian Islands or New Zealand have generated a plethora of research findings and ideas on managing invasive species more proactively and strategically (Daehler et al. 2004; Hulme 2020).

The ecology of mountain invasions resembles island invasion ecology in a variety of ways, as mountains represent habitat islands in the mainland seas they rise above. Mountains tend to be more inaccessible to human habitation and thus have often been subject to low levels of anthropogenic impacts by comparison to other habitats (McDougall et al. 2011; Lembrechts et al. 2017). Unfortunately, human interference in mountain ecosystems is growing due to climate change, land use change, technology, increased trade, and global connectivity, and some of this interference has been manifested as increased levels of invasive species in mountainous regions (Chap 13). Because invasive species, once introduced, can spread on their own, seemingly inaccessible places in human terms, like many mountain landscapes, are not at all immune to invasive species. Seemingly small changes to infrastructure, such as the establishment of roadways in mountains, have been shown as a natural gateway to invasive plants through disturbance effects and dispersal via vehicles (McDougall et al. 2018; Rew et al. 2018). As with oceanic islands, mountain habitats often cover relatively small areas and have unique features, which make them very sensitive to the effects of invasive species. Most management strategies and challenges for invasive plants occurring in mountains are similar to those in other areas, although the remoteness and inaccessibility of mountain landscapes present unique challenges for surveying for and managing mountain invasive plants (Giljohann et al. 2011; McDougall et al. 2018).

1.4 Assessing Invasive Plant Impacts

1.4.1 Social, Economic, and Environmental Impacts

Assessment of the impacts of invasive species has often been described as one of the weakest links in the field of invasion science (Hulme et al. 2013). Sometimes this is due to a lack of concrete evidence to support the assumption of their damaging effects (Hager and Mccoy 1998; Lavoie 2010; Vilà et al. 2011; Epanchin-Niell 2017; Diagne et al. 2021; Chap 14). Advocates attempting to lobby for resources needed to manage invasive species may be challenged to come up with a clear message in the absence of good data on impacts. It is true that information available on social, environmental, and economic impacts of invasive plants is relatively scarce and there is a need for better assessment of these impacts (Chap 14). However, through the innovative development of new databases like InvaCost and various other efforts to quantify impacts, agencies and researchers are endeavoring to better assess the cost of invasive species to the economy, ecosystems, and society (Blackburn et al. 2014; Hawkins et al. 2015; Pyšek et al. 2017; Bacher et al. 2018; Diagne et al. 2020, 2021; Chap 14).

Innovative methodology and approaches to measure and better assess biotic impacts are being developed (Probert et al. 2020b). The biology and ecology of most major invasive plant species is relatively well known (e.g., Adkins and Shabbir 2014; Day et al. 2016; Gillies et al. 2016; Coetzee et al. 2017; Anderson 2019). However, we are just beginning to understand these species in enough depth to quantify their biotic impacts and design appropriate management measures, including consideration of their impacts on endangered species (Bellard et al. 2016, 2017; Foxcroft et al. 2017; Blackburn et al. 2019; Duenas et al. 2021; Chap 14). Recently, efforts have been made to develop a better classification system for invasive species, to rank them according to either socioeconomic or environmental impacts, in order to develop a more objective assessment for the purposes of research and management (Blackburn et al. 2014; Hawkins et al. 2015; Bacher et al. 2018; Probert et al. 2020b). Moreover, the issues extend beyond scientific understanding. Various stakeholders frame invasive species management very differently depending on their respective values, reflecting a critical need for the development of better ways to engage stakeholders to hear all points of view and communicate the science more honestly and effectively (Courchamp et al. 2017; Novoa et al. 2018). It is also important to recognize that the human side of the management of invasive species generally involves a complex "ecology" of its own, i.e., "social-ecological systems" (Hui and Richardson 2017; Shackleton et al. 2019). These systems may best be seen as "complex adaptive systems" consisting of many moving parts, so that management is more than just asking: "What does the science say?" Rather, management needs to consider a more holistic, socioeconomic response to invasion, respecting the values of various agencies, special interest groups, and other stakeholders, which together make up an evolving complex system (Hui and Richardson 2017).

One of the most important questions for many of these stakeholders is: "Are invasive plants really that bad?"

1.4.2 Are Invasive Plants Really that Bad?

The two extreme views on impacts of non-native plants are "innocent until proven guilty" and "guilty until proven innocent." Both scientists and practitioners, and for that matter, the general public, may hold either view or adhere to a position somewhere in the middle of the two extremes (Courchamp et al. 2017; Novoa et al. 2018; Cassini 2020). The position a given person holds may depend on attributes of a particular invasive species, and hence the value of a system of classifying non-native species according to socioeconomic or environmental impacts, although biases may still arise in the classification process (Probert et al. 2020b). Although acknowledging that the impacts of invasive species may be difficult to assess and quantify, Simberloff et al. (2013) maintained that regardless of impact, non-native origin of a species is an important consideration, because frequently non-native species exhibit a lag in their impacts and/or may be having socioeconomic or environmental impacts that are undetected. By contrast, other scientists have insisted that the degree of impact should be part of the definition of an invasive species, with low or no impact species should be classed as benign (Davis and Thompson 2001; Davis et al. 2011). The quest for a more realistic assessment comes partly from a critical examination of invasive species biology, often coming from those who believe non-native species are innocent until proven guilty. This critical examination has sometimes been referred to as "invasive species denialism" (Ricciardi and Ryan 2018). Since the 1990s, coinciding with the growth of the field of invasive biology, scientific articles, books, and the popular press have been increasingly questioning the warnings by invasion biologists (Richardson and Ricciardi 2013). This in turn is viewed by some as a threat to the good work done by researchers and practitioners in the field (Russell and Blackburn 2017; Ricciardi and Ryan 2018) while to others a healthy dose of realism serving to refine the science of invasion biology (Sagoff 2018; Munro et al. 2019; Davis 2020). Courchamp et al. (2017) provide some helpful guidelines for potentially resolving some of the issues in invasion biology, including utilizing a dialog model for knowledge mobilization in place of a deficit model that assumes that greater exposure to the science from experts will eventually convince members of society that the experts are right. The dialog model provides for two-way discussions among scientists, government, trade and industry stakeholders, and the general public to address challenging issues such as how best to classify a species as invasive.

How non-native species are classified has implications for their management. If they are considered "guilty until proven innocent," more immediate attention will be given to recent arrivals, with more active management recommended for species labeled as invasive. Such a universal stance over invasive status has been critiqued as a knee-jerk reaction to a species being "non-native" or "alien," potentially leading to inappropriate attitudes or management actions towards a given species just because it is non-native, which may even result in harm to the ecosystem (Zavaleta et al. 2001; Bergstrom et al. 2009). There is a growing body of data on how bad invasive plants are, such as the meta-analysis by Kuebbing and Nuñez (2018) looking at plant interactions between 274 vascular plants in 21 habitats, finding that the negative effect of non-native neighbors was twice as bad for natives than for non-natives. In defense of the validity of the result, Kuebbing and Nuñez (2018) pointed out that although there is disagreement on the incorporation of impact into the definition of invasiveness, it has been shown how impacts increase with increased spread and populations (Simberloff et al. 2013; Hulme et al. 2013). Indeed there is evidence that much of the perceived uncertainty in assessments of invasive species impacts is misguided (Hulme et al. 2015; Wilson et al. 2016; Pauchard et al. 2018; Courchamp et al. 2020).

The application of a classification system based on a scientific assessment of risk or impact (McGregor et al. 2012; Probert et al. 2020b) may result in a more nuanced response based on "how bad" the invasive plant is likely to be in the invaded range. Two unified schemes have been developed to evaluate impacts, utilizing information from the literature and other relevant sources on either environmental (Blackburn et al. 2014; Hawkins et al. 2015) or socioeconomic impacts (Bacher et al. 2018), both featuring five levels of impact: minimal, minor, moderate, major and massive (Table 1.1). The environmental impacts are rooted in the mechanisms used by the International Union for Conservation of Nature (IUCN) Global Invasive Species Database to evaluate invasive species impacts (Blackburn et al. 2014), while the socioeconomic impacts are based primarily on assessments of how the well-being of people is affected by the invasive species (Pejchar and Mooney 2009; Bacher et al. 2018). Clearly, the magnitude of environmental and socioeconomic impact will not always match for a given species, but information from both types of analysis is useful in formulating management approaches (Bacher et al. 2018).

"Massive," the highest level in these impact assessments, involving irreversible environmental and/or socioeconomic impacts (Table 1.1) may be difficult to appreciate without reference to actual examples. Some good examples of truly massive impacts of invasive plants are found among the 37 plant species selected as part of the list of the 100 worst invasive alien species compiled by the IUCN in 1999 to raise awareness of the risks posed by such species (Lowe et al. 2000; Luque et al. 2014; Table 1.2; Fig. 1.2). Note that this list was never meant to encompass the top

100 worst but rather to communicate that these species are among the worst alien invasive species (Luque et al. 2014). Impacts of the 37 plants on the list range widely but commonly include impacts on native flora and associated fauna, while many also have impacts on agricultural through similar competitive mechanisms, with many of the species classed as fast growing (Table 1.2). These invasive plants are primarily perennial, with many of them consisting of woody perennials with a tendency to form large patches or thickets that are difficult to manage and may cause irreversible changes to ecosystem functions, consistent with the criteria for massive impacts in the IUCN Environmental Impact Classification for Alien Taxa (Table 1.1). Among them are also some of the worst invasive plants in non-terrestrial habitats, such as common water hyacinth and salvinia (*Salvinia molesta*), with the latter added to the top 100 worst alien invaders list to replace the rinderpest virus that was removed when it was declared to be eradicated globally in 2010 (Luque et al. 2014).

Table 1.1 Comparison of the range of impacts of invasive species according to two impact classification schemes: the IUCN Environmental Impact Classification for Alien Taxa (EICAT) (Blackburn et al. 2014; Hawkins et al. 2015) and the Socio-economic Impact Classification of Alien Taxa (SEICAT) (Bacher et al. 2018)

Level of impact	Type of impact assessment	
	Environmental Impact Classification for Alien Taxa (EICAT)	Socio-economic Impact Classification of Alien Taxa (SEICAT)
Minimal	Unlikely to have caused deleterious impacts on the native biota or abiotic environment	No deleterious impacts reported despite availability of relevant studies with regard to its impact on human well-being
Minor	Causes reductions in the fitness of individuals in the native biota but no declines in native population densities	Reductions of well-being can be detected, e.g., income loss, health problems, higher effort, or expenses to participate in activities
Moderate	Causes decline in the population density of native species but no changes to the structure of communities or to the abiotic or biotic composition of communities	Negative effects on well-being leading to changes in activity size, fewer people participating in an activity, partial displacement, abandonment, or switch of activities do not increase human well-being (no increased opportunities due to alien spp.)
Major	Causes the local or population extinction of at least one native species and leads to reversible changes in the structure of communities and the abiotic or biotic composition of ecosystems	Local disappearance of an activity from all or part of the area invaded by the alien taxon; change is likely to be reversible within a decade after removal or control of the alien taxon
Massive	Leads to the replacement and local extinction of native species and produces irreversible changes in the structure of communities and the abiotic or biotic composition of ecosystems	Local disappearance of an activity from all or part of the area invaded by the alien taxon; change is likely to be permanent and irreversible for at least a decade after removal of the alien taxon

1.5 The Way Forward

For most invasive plants, there is no systematic long-term international strategy like the global campaign mounted to eradicate the bovine rinderpest virus, formerly listed as one of the 100 worst alien invaders by the IUCN (Luque et al. 2014). The eradication effort was ultimately successful after more than a decade of concerted action involving many agencies and a massive

Table 1.2 The 37 plants listed in the International Union for Conservation list of the 100 worst invasive alien species worldwide (Lowe et al. 2000), including the later addition of salvinia (*Salvinia molesta*) (Luque et al. 2014), with impact summaries derived from the ISSG (International Species Specialist Group) Global Invasive Species Database http://www.iucngisd.org/gisd/ and personal observations of the authors

Common name	Latin name	Impact summary
African tulip tree	*Spathodea campanulata*	Evergreen tree native to West Africa introduced throughout the tropics, as an invasive threat to native vegetation in many of the Pacific Islands
Black wattle	*Acacia mearnsii*	Fast-growing nitrogen-fixing tree native to Australia competes reducing native biodiversity in parts of Africa, Eurasia, and the Pacific Islands
Brazilian pepper tree	*Schinus terebinthifolius*	Evergreen shrub or small tree, native to Brazil, produces deep shade and alters the natural fire regime in numerous oceanic islands
Caulerpa seaweed	*Caulerpa taxifolia*	Marine alga widely used as a decorative aquarium plant forming dense monocultures excluding most other marine life; cold-tolerant strain, inadvertently introduced into the Mediterranean Sea, spread over more than 13,000 hectares of seabed
Cogon grass	*Imperata cylindrica*	Native to Asia; considered one of the world's ten worst weeds, has spread to most warm temperate zones worldwide; extensive rhizome system, adaptation to poor soils, drought tolerance, genetic plasticity, and fire adaptability make it a threat to many ecosystems
Common cord-grass	*Spartina anglica*	Perennial salt marsh grass, product of hybridization with European cord-grass; excludes native plant species and degrades wildlife habitat in the invaded range in Europe and New Zealand
Cluster pine	*Pinus pinaster*	From the Mediterranean Basin, now invades natural shrubland, forest and grassland in many temperate regions, suppressing native plants and altering fire regimes and hydrology
Erect prickly pear	*Opuntia stricta*	A cactus up to 2 m in height from Central America, considered to be Australia's worst ever weed, also invasive in South Africa
Fire tree	*Morella faya*	Fast growing, N-fixing tree native to the Azores, Madeira Islands, and the Canary Islands, introduced to Hawaii, New Zealand, and Australia forming dense stands and altering N cycles
Giant reed	*Arundo donax*	Native to Asia, invades riparian areas worldwide, altering the hydrology, nutrient cycling, and fire regime and displacing native species
Giant salvinia	*Salvinia molesta*	Floating aquatic fern native to South America that thrives in slow-moving, nutrient-rich, warm freshwater, cultivated by aquarium and pond owners, forming massive, thick mats in wetlands on a massive in its introduced range throughout the world

(continued)

Table 1.2 (continued)

Common name	Latin name	Impact summary
Gorse	*Ulex europaeus*	A spiny, perennial, evergreen shrub from Europe now established in Mediterranean and subtropical climate zones throughout the world (including North America, New Zealand, Africa, and Asia) displacing cultivated and native plants and altering soil conditions and fire regimes
Hiptage	*Hiptage benghalensis*	A liana native to southern Asia, invasive in Australian rainforests, Mauritius and Réunion, forming impenetrable thickets and smothering native vegetation
Japanese knotweed	*Reynoutria japonica*	Herbaceous perennial native to Japan naturalized in Europe and North America found primarily in moist habitats but also in waste places, along roadways and other disturbed areas; hybridizes with *R. sachalinensis* to form hybrid *R.* × *bohemica* which is even more invasive than *R. japonica*
Kahili ginger	*Hedychium gardnerianum*	Showy ornamental native to the Himalayas which grows over 2 m tall in wet tropical climates displacing native plants in the parts of Africa, Asia, and on oceanic islands
Koster's curse	*Clidemia hirta*	Invasive shrub native to the Neotropics, now occurring widely on oceanic islands in the Pacific and Indian oceans invading forest gaps, preventing native plant species from regenerating

(continued)

Table 1.2 (continued)

Common name	Latin name	Impact summary
Kudzu	*Pueraria montana* var. *lobata*	Invasive vine native to Southeast Asia, infesting large areas of the southern United States but also naturalized through parts of Europe, Africa, and various oceanic islands, impacting forestry and property values
Lantana	*Lantana camara*	A significant weed native to central and South America with some 650 varieties distributed in over 60 countries impacting both agriculture and natural ecosystems severely through infesting the forest understory or disturbed areas
Leafy spurge	*Euphorbia esula*	Herbaceous perennial native to Europe and temperate Asia, now found throughout the world, with the exception of Australia displacing native vegetation and crops through shading and competition
Leucaena	*Leucaena leucocephala*	Fast-growing, N-fixing tree/shrub native to Central America widely introduced for its beneficial qualities as a forage but is also an aggressive invader in disturbed areas in many tropical and subtropical locations globally
Mesquite	*Prosopis glandulosa*	A perennial, woody, deciduous shrub or small tree native to Mexico and the southern United States, now introduced throughout the world, particularly invasive in Australia and South Africa, forming impenetrable thickets that compete strongly with native species

(continued)

Table 1.2 (continued)

Common name	Latin name	Impact summary
Miconia	*Miconia calvescens*	Small tree native to tropical America now considered one of the most destructive invaders in insular tropical rain forest habitats in its introduced range in the Pacific Islands, where it outcompetes native vegetation and increases soil erosion
Mile-a-minute weed	*Mikania micrantha*	A perennial creeping climber native to central and South America that grows rapidly under optimal conditions competing for light and smothering native plants and crop plants, widespread in its introduced range in southern Asia and the Pacific Islands
Mimosa	*Mimosa pigra*	Shrub native to central and South America, particularly invasive in parts of South East Asia and Australia, often spreading through natural grassland floodplain ecosystems and pastures, converting them into unproductive scrubland
Privet	*Ligustrum robustum*	Shrub native to southern Asia, disrupting primary forest regeneration and floral biodiversity in oceanic islands, e.g., Mauritius and Réunion
Pumpwood	*Cecropia peltata*	Fast-growing tree native to Neotropical regions, rapidly invading disturbed areas, in its invaded range, e.g., Malaysia, Africa, and Pacific Islands

(continued)

Table 1.2 (continued)

Common name	Latin name	Impact summary
Purple loosestrife	*Lythrum salicaria*	An erect perennial wetland herb native to Eurasia, spreading widely in wetlands in its introduced range in North America, forming monocultures and displacing native vegetation
Quinine tree	*Cinchona pubescens*	Widely cultivated tropical forest tree native to central and South America but escapes and outcompetes native vegetation in Pacific Islands, e.g., the Galapagos Islands
Shoebutton ardisia	*Ardisia elliptica*	Fast-growing evergreen tree native to South Asia with fast growth that escapes cultivation especially via frugivory to invade natural areas in its introduced range, e.g., various Pacific islands
Siam weed	*Chromolaena odorata*	Fast-growing perennial shrub, native to south and Central America introduced into the tropical regions of Asia, Africa, and the Pacific, where it forms dense stands that prevent the establishment of other plant species and is also a nuisance weed in agricultural land and commercial plantations
Strawberry guava	*Psidium cattleianum*	Thicket-forming tree native to Brazil, naturalized in Florida, Hawai‘i, tropical Polynesia, Norfolk Island, and Mauritius having devastating effects on native habitats in Mauritius and Hawai‘i

(continued)

Table 1.2 (continued)

Common name	Latin name	Impact summary
Salvinia	*Salvinia molesta*	Free-floating aquatic fern native to Brazil, it forms dense vegetation mats reducing water flow and negatively affects the biodiversity and abundance of freshwater species
Tamarisk	*Tamarix ramosissima*	Rampantly invasive shrub native to Asia that may dominate riparian zones of arid climates in North America, South America, Africa, and Australia; depletes water sources, and increases erosion and flood damage, soil salinity, and fire potential
Wakame seaweed	*Undaria pinnatifida*	Kelp native to Japan where it is cultivated for human consumption, but invades worldwide via fouling ship hulls, now infesting Atlantic, Pacific, and Mediterranean coastal ecosystems
Water hyacinth	*Eichhornia crassipes*	Aquatic weed originating in South America, now found in more than 50 countries on 5 continents, rapidly infesting and impacting waterways, limiting boat traffic, swimming, and fishing
Wedelia	*Sphagneticola trilobata*	Mat-forming perennial herb native to Central America and naturalized in many wet tropical areas of the world; readily escapes from gardens and forms a dense ground cover, preventing native species establishment and reduces agricultural yields
Yellow Himalayan	*Rubus ellipticus*	Thorny shrub from southern Asia naturalized in Hawai'i southern United States raspberry and the United Kingdom, forming thick patches and outcompeting native species

program of vaccination and other measures (Morens et al. 2011). Invasive plants are very different organisms than viruses in terms of biology and ecology, and furthermore it is much more difficult to mount a unified, focused effort in most cases because opinions vary on the seriousness of the problem. Nevertheless, progress has been made and strategies are being devised (Pyšek et al. 2020; Chaps 15 and 16). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is tasked with performing a global assessment, comprehensively examining threats posed by invasive alien species, and making recommendations for policy and management by 2023 (Brondizio et al. 2019; Pyšek et al. 2020).

1.5.1 Techniques and Global Strategies

Members of the general public commonly think about weed control in terms of very basic tools like hand-weeding, using a hoe or a shovel, or perhaps utilizing herbicides. However, far more sophisticated tools and management approaches are now available (Chap 15). In fact, before one even picks up a hoe or some other tool, there are salient management tools that may be deployed in view of the complexities around invasive species. One such tool is "horizon scanning" which strives to look futuristically at "thorny problems"