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General Introduction – Aquatic and Terrestrial Biological Invasions in the 21st Century

Motivation and Book Structure

In the preface of his 2007 book, Wolfgang Nentwig (Nentwig, 2007) starts by posing an obvious question: "*Yet another book on biological invasions?*". In fact, the market already provides several valuable volumes focusing on biological invasions in both aquatic and terrestrial systems (e.g. Mooney *et al.*, 2005; Lockwood *et al.*, 2006; Davis, 2009; Rilov & Crooks 2009a; Richardson, 2011; Simberloff, 2013). However, invasion science is a dynamic discipline and new detection tools, modeling techniques, and eradication and management strategies have been developed and updated in recent years. For example, in the past 20 years, molecular genetic approaches have been increasingly used to investigate the origin and rapid evolution of non-indigenous species (NIS) and other biological invasion processes (Geller *et al.*, 2010; Darling, 2015). These DNA tools have recently been used to detect NIS, in taxonomic identification, to elucidate sources and vectors of introductions, to monitor NIS expansions in invaded regions, and to describe the consequences of introductions for native communities (Razgour *et al.*, 2013; Darling, 2015). Furthermore, modeling techniques have been developed in recent years to forecast spatial and temporal patterns of NIS distributions in future climate change scenarios (see also Chapter 17).

In this context, the present book integrates with the current questions and hypotheses being postulated in invasion science in a timely approach (Sax *et al.*, 2005; Rilov & Crooks 2009a; Galil *et al.*, 2011). It is generally accepted that a better understanding of the processes controlling the success of invasive species and what processes will influence their persistence in space and time will contribute to improved tools for environmental managers seeking to reduce or prevent invasions of new species.

In this book, a collection of efforts from 57 renowned worldwide invasion scientists covers our current knowledge of biological invasions as well as their impacts, patterns and mechanisms in marine, freshwater and terrestrial ecosystems. The book presents a multidisciplinary approach to biological invasions with key study cases from different biogeographic regions structured into four sections. In Part I – 'Biogeography and vectors of biological invasions', six chapters characterize several vectors of introduction of non-indigenous species as well as spatial and temporal scale patterns of invasions across different ecosystems and taxonomic groups.

Part II – 'Biological invasions in aquatic ecosystems and in host parasite systems', comprised of five chapters, is dedicated to invasions in aquatic ecosystems but also to the significance of parasites in the context of biological invasions. Furthermore, the four chapters included in Part III – 'Management and control of biological invasions' have a strong emphasis on different behaviors of well known invasive species and further discuss possible management tools and future advice for preventing and controlling this global environmental threat. Finally, the closing four chapters included in Part IV – 'Predictions and new tools in biological invasions' looks into the future of biological invasions. In this final section, contributions emphasize emerging molecular tools, climate change, and modeling techniques.

Brief Discipline History

Naturalists have likely been observing and thinking about biological invasions in some form or other for centuries. Indeed, Charles Darwin, Charles Lyell and Frank Egler all referred to invasive species in their work (Richardson, 2011). However, it was the pioneering and influential work of British ecologist Charles Elton (Elton, 1958) that first drew attention to the phenomena of biological invasions and, more importantly, their impacts on local communities and ecosystems. Since Elton's milestone work, a growing number of volumes across ecosystems and biogeographic regions have been contributing to strengthen the study of biological invasions (e.g. Mooney *et al.*, 2005; Lockwood *et al.*, 2006; Nentwig, 2007; Davis, 2009; Rilov & Crooks 2009a; Richardson, 2011; Simberloff, 2013). Likewise, a few scientific journals (e.g. *Biological Invasions*, *Aquatic Invasions, NeoBiota* or *BioInvasions Records*) and conferences (e.g. *International Conference on Marine Bioinvasions* or *NeoBiota - European Conference on Biological Invasions*) are exclusively dedicated to the study of biological invasions.

Moreover, and for example in the marine system, NIS have received great attention from scientists, managers and policy makers. As a result, this global problem has been addressed from different angles in various EU-funded FP6 and FP7 projects (ERNAIS, 2001; ALARM, 2008; DAISIE, 2008; VECTORS, 2011; INVASIVES, 2013). Valuable work has also proceeded on several regional concepts focused on databases and management (NEOBIOTA, 1999; REABIC, 2001; NOBANIS, 2012; AquaNIS, 2013). Recently, the European Marine Strategy Framework Directive (MSFD) has also included NIS among key descriptors required for assessing and setting a qualitative target - Good Environmental Status (GES).

Finally, the interest of the general public in this global problem is increasing and this is reflected in the intensification of media coverage on biological invasions, including television shows, magazines, newspapers and blogs, and many others.

The Invasion Process

When organisms are deliberately or accidentally introduced into a new ecosystem a biological invasion may take place. Whether in land or water, to successfully invade an ecosystem or a community, these so-called ‘invasive species’ have to pass through a series of stages known as the ‘invasion process’ (Lockwood *et al.*, 2006). The first stage of this process can be seen as the ‘transport phase’ where a particular species is transported (intentionally or unintentionally) from their native range to a new area and released into the wild. Second, arriving into a new environment, individuals must establish a viable population (‘establishment phase’), or the population becomes extinct. Third, this now-established population of invasive individuals needs to increase in abundance and expand its geographic range (‘spread phase’), otherwise it remains in low abundances and with only a small local distribution. Finally, once this invasive population is able to establish and spread its distribution range, the population will then alter the invaded community causing ecological and economic impacts (‘impact phase’). The capacity of a given invader to pass each of these stages dictates the success of an invasion.

Nowadays, there are several cases of successful invasive species both in aquatic and terrestrial systems, that due to their impacts (ecological and/or economic) have become famous worldwide. A good example in the marine system is the well-documented invasion of the Indo-Pacific lionfish *Pterois volitans* and *Pterois miles* (featured in this book cover) into the Western Atlantic and Caribbean. The first sighting of this marine invader was reported in Florida in 1985, and since their establishment in the Bahamas in 2004, they have colonized more than 7 million km^2 in the Western Atlantic and Caribbean (Côté *et al.*, 2013). In the terrestrial system, the cane toad *Bufo* [*Rhinella*] *marina* is probably considered the most famous and iconic invader (see Chapter 13). These toads are native to South and Central America and have been moved to several countries to (unsuccessfully) control insect pests. These toads were introduced to Australia in 1935 and have since spread across several regions of the continent with severe ecological and economic impacts (Chapter 13).

Challenges in the 21st Century

Once successful, biological invasions by animals, plants or pathogens are one of the greatest environmental and economic threats and, along with habitat destruction, a leading cause of global biodiversity loss (Mack *et al.*, 2000). In addition, the rate of detected invasions in terrestrial and aquatic ecosystems has increased significantly in the last two decades for several reasons: 1) search effort, which follows the establishment of specialized research groups in different continents and across different disciplines; 2) the development and use of new emerging molecular approaches; and 3) climate change.

The growing interest in invasion science in the 21st century is reflected in a simple and original literature survey I performed for this introductory account. To verify the growing interest in biological invasions in this century I conducted a simple search at "Web of Science" for articles published between 2000 and 2014 that included the keywords 'invasive' OR 'invasion' OR 'non-native' OR 'alien' as the main topic. To avoid any bias with medicine and cancer research due to the use of the terms 'invasive' and 'invasion', I restricted the search to the following research areas: ecology, biology, limnology, fisheries, forestry, plant sciences, marine freshwater biology, biodiversity and conservation, environmental sciences, oceanography, entomology and zoology. The results of this literature survey show that a total of 36344 articles on biological invasions were published from 2000 to 2014 with a growing tendency over the years (Figure G1A). Lockwood *et al.* (2006) performed a simple meta-analysis where they also show an increasing pattern on the number of citations returned from a search on the Science Citation Index between 1975 and 2004 within the field of invasion ecology. The results I show here corroborate the same tendency after 2004 but it seems the number of papers appear to stabilize after 2011 at a rate of a little below 4000 papers per year (Figure G1). Interestingly, the United States of America is the country that contributes by far the most scientific articles on biological invasions, followed by Australia and Canada (Figure G1B). China and European countries such as England, France, Germany, Spain and Italy complete the top 10 territories that contribute the most to the scientific body of knowledge on this phenomenon. Finally, the majority of these contributions are in the field of Environmental Sciences and Ecology with more than 16000 papers in the course of 15 years (Figure G2). Marine and Freshwater Biology, as well as Plant Sciences, are also well represented with approximately 6000 contributing papers between 2000 and 2014.

For the coming years, I expect that the interest in biological invasions will continue, with the production of more scientific papers and an increase in citations. New records and detections of non-indigenous species will probably continue in the next decades in several biogeographic regions, both in aquatic and terrestrial ecosystems. New emerging techniques such as molecular approaches and spatial and temporal modeling will play a key role in producing a significant amount of papers in coming years. However, the slope of increase in publication rate will probably decrease in future years as can already be seen in Figure G1A after 2010.

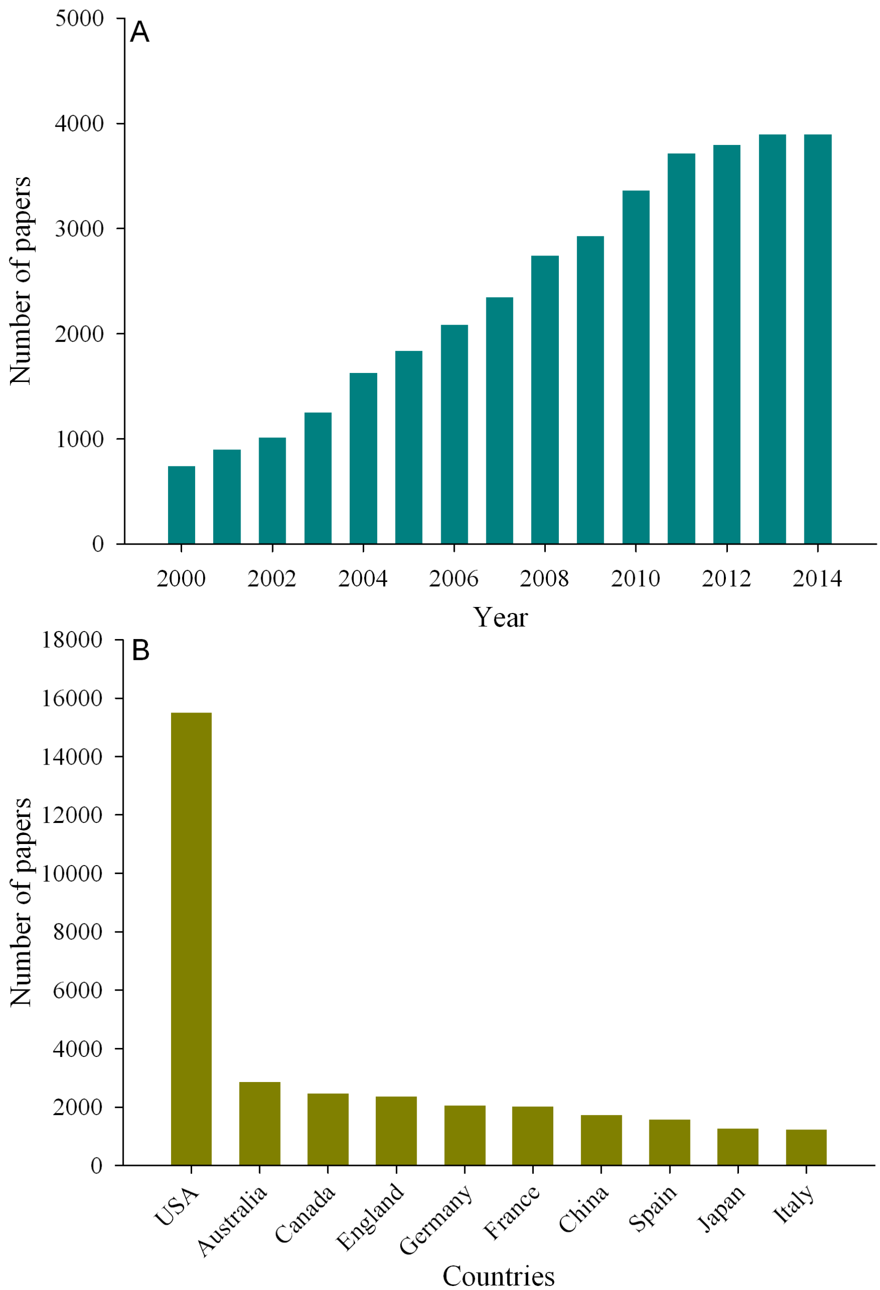

Fig. G1: Number of articles published in invasion science from 2000 to 2014 for this literature search (A) and most represented countries contributing to the field in the 21st century (B).

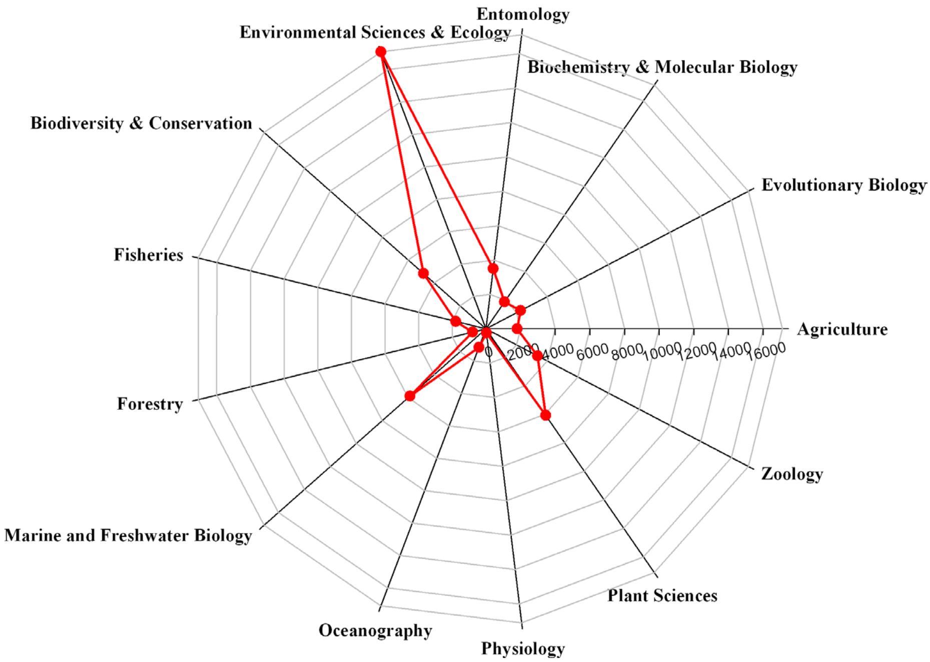

Fig. G2: Most represented research areas in papers published between 2000 and 2014 in biological invasions from a literature survey I performed in "Web of Science".

A Final Note on Definitions and Invasion Terminology

In recent years there have been several efforts trying to achieve harmony and consistent usage in terminology within invasion biology and ecology (e.g. Occhipinti-Ambrogi & Galil, 2004). This much-needed consistency in bioinvasion terms would likely facilitate debate about this issue for the scientific community, but also for policy makers, managers and the general public. Below I outline a few key terms now being used in invasion science:

Non-Indigenous Species (NIS): I personally have preference for this designation as it describes a given species that was moved outside its usual geographical range via anthropogenic actions (this could be intentional or accidental), irrespective of its impact on native species and native ecosystems.

Invasive species: an invasive species by definition must be a NIS, but one that has caused demonstrable impact, both in ecological and economic terms.

Cryptogenic species: this is a species of unknown origin or a species that is neither undoubtedly native nor NIS.

Native species: this term refers to a species that occurs naturally in a given area/ecosystem/region. These species were not introduced via human actions, either intentionally or accidentally.
Biological invasion or bioinvasion: This is a very broad term that refers to the introduction of NIS into new ecosystems/area/regions via human actions but also considers natural range expansions.
Propagule pressure: this term can be seen as the introduction effort, i.e. the pool of individuals introduced in a new ecosystem/area/region and the number of times it is released.

However, concepts currently used in invasion science are highly unlikely to ever reach national or international uniformity because they vary among scientific disciplines, countries, and linguistic borders (Carlton, 2002; Occhipinti-Ambrogi & Galil, 2004; Rilov & Crooks, 2009b). In future years, I expect invasion biologists and scientists will continue to employ i) the same word that probably means distinctive things to different workers; but also ii) different words that mean the same thing. A good example of this is the word '*invasive*', which could imply a species with documented ecological and economical impact in a certain region or simply suggest nothing more than an '*exotic*', '*alien*' or '*non-indigenous species*'. A further example would be the definition of '*propagule pressure*' which, for certain scientists, simply defines the term quantitatively as the number of individuals introduced in a new area and the number of times an invader is released. In contrast, to other authors '*propagule pressure*' could imply a much broader concept, including propagule viability and other parameters such as stress tolerance. In this context, I decided not to attempt any consistency in invasion terms for the current volume and, as such, all authors in this book have used invasion-related terms of their own choosing.

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