Aquatic Invasions (2014) Volume 9, Issue 4: 521–528
doi: http://dx.doi.org/10.3391/ai.2014.9.4.10

Open Access

Research Article

An analysis of publications on invasive macrophytes in aquatic ecosystems

Heloísa B.A. Evangelista[1]*, Sidinei Magela Thomaz[1] and Cristiane Akemi Umetsu[2]

[1]*Núcleo de Pesquisas em Limnologia Ictiologia e Aquicultura, Departamento de Biologia, Universidade Estadual de Maringá, Av. Colombo, 5790, CEP 87020-900, Maringá, PR, Brazil*

[2]*Programa de Pós-graduação em Aquicultura, Universidade Estadual Paulista, Jaboticabal, São Paulo CEP 14884-900, Brazil*

**Corresponding author*

E-mail: helobeatriz@gmail.com

Received: 4 December 2013 / Accepted: 20 August 2014 / Published online: 1 October 2014

Handling editor: Vadim Panov

Abstract

In this study, we performed a scientometric analysis of published scientific papers on the biological invasion of macrophytes in freshwater ecosystems to assess the main trends and gaps in research concerning this group of organisms. The analysis showed that publications on invasive macrophytes increased exponentially in the last decade. However, the activity index (a comparison of the quantitative trends of invasive macrophytes in relation to all of the papers on macrophytes) indicated that invasive macrophytes have not been consistently studied more than other topics in the field of limnology over the last decade. The most studied macrophyte species were *Myriophyllum spicatum, Hydrilla verticillata, Phragmites australis* and *Eichhornia crassipes*. Certain gaps were related to the limited number of studies on the important species threatening tropical ecosystems, under-representation of investigations on the impacts of invasive macrophytes on fish and lack of studies associating macrophytes with microorganisms (bacteria and fungi). Studies that encompassed several levels of biological complexity were also scarce, indicating that the studies were fragmented at specific levels. Finally, there was a clear geographical bias, with fewer studies occurring in Neotropical and Afrotropical regions. Identification of these gaps may be useful for addressing future studies that might help evaluate the causes of invasion by macrophytes and the impacts of such invasions on freshwater ecosystems.

Key words: exotic plants, non-native macrophytes, invasibility, invasiveness

Introduction

In general, most of the attention directed towards invasion biology is devoted to terrestrial organisms instead of aquatic organisms (Davis 2000; Jeschke et al. 2012). Specifically, plants have been the most studied group in terrestrial environments (Pysek and Richardson 2006; Pysek et al. 2008). Among the studies related to terrestrial environments, we highlight the long-term studies of systems such as forests (Matlack and Schaub 2011) and studies of pests in agriculture (Hummel et al. 2002) to illustrate the greater concern for the conservation and restoration of environments and systems of direct economic importance (Steedman et al. 1996). However, studies of aquatic ecosystems are scarce when considering their ecological and economic importance (Johnson et al. 2009; Jeschke et al. 2012). Furthermore, compared to terrestrial ecosystems, aquatic ecosystems have a higher diversity per unit area (Balian et al. 2008), higher rate of extinction (Jenkins 2003), and appear to be especially vulnerable to invasive species (Sala et al. 2000; Capers et al. 2007). Thus, the assessment of causes and consequences of invasions are especially relevant in these ecosystems.

Macrophytes have adaptations that enable their rapid spread and growth (Santamaria 2002) and increase their invasive potential. Furthermore, these organisms are important in structuring aquatic environments, promoting increased habitat complexity at different scales and supporting the functional diversity of other assemblages (Taniguchi et al. 2003). Freshwater ecosystems are highly impacted by human beings (e.g., through eutrophication), which increases the invasibility of these systems by macrophytes (Engelhardt 2011).

Successful macrophyte invaders have caused severe damage to rivers, lakes, wetlands and reservoirs. The impacts caused by macrophytes may extend from plant communities (e.g., Madsen et al. 1991) to other trophic levels (e.g., Theel et al. 2008) and even entire ecosystems (e.g., Yarrow et al. 2009). Because of the importance of these

plants in transforming aquatic ecosystems, the identification of gaps in the literature on invasive macrophytes is still required to better address future studies designed to determine the causes and effects of macrophyte invasions.

In the current study, we intend to answer the following questions: *i)* What is the temporal trend in publications on biological invasions related to aquatic macrophytes? *ii)* What species, life forms, biogeographic regions and approaches (e.g., theoretical, experimental or observational) receive the most focus? *(iii)* What level of organisation (genetic, population, community and ecosystem) and what communities associated with invasive aquatic macrophytes are studied most frequently? Thus, the aim of this study is to understand the characteristics of the scientific literature related to aquatic invasions by macrophytes and determine the scientific gaps in the field.

Materials and methods

A survey was conducted in January 2013 using the Thomson Reuters database (ISI Web of Science, http://thomsonreuters.com/thomson-reuters-web-of-science/) and applying the following combinations: ("macrophyte*" OR "aquatic plant*") AND ("exotic* "OR" inva*") to filter words such as macrophyte, macrophytes, aquatic plant, aquatic plants, invasion, invader, invasibility, invasiveness and invasive or exotic in the search fields by title, abstract and keywords. Only studies that treated macrophytes as exotic, invasive or both were considered. Articles from 1970 to December 2012 were separated into five-year periods and eight groups for analysis; 890 articles were found, and 533 were retained for further analysis. The remaining articles contents did not match our goals. Based on this dataset, we evaluated the number of articles published per five-year period and the number of articles published in different journals.

During the five-year periods from 1976–1980 and 1981–1985, we did not find any articles related to invasive macrophytes. However, because of the large number of items analysed in other years (533 articles), a random sampling was conducted of 30% of the items for each five-year period to maintain the proportional representation of each period. We also found only one article from the five-year periods from 1970–1975 and 1986–1990, and it was retained for further analysis. This sampling procedure resulted in 161 articles, which were fully analysed (Appendix 1).

We classified the articles according to the following topics: (*i*) species of studied exotic and/or invasive macrophytes, (*ii*) the taxonomic group or assembly associated with the studied exotic and/or invasive macrophyte, (*iii*) type of study *(*observational/*in situ*, experimental (*in situ* or in laboratory/greenhouse) or theoretical, and (iv) the level of organisation that was investigated. Regarding the last topic, we divided the studies into four organisational levels (according to Parker et al. 1999; Gherardi 2007): (*i*) population dynamics (e.g., abundance and population growth), (*ii*) genetics (including hybridisation), (*iii*) community (e.g., richness, diversity and trophic structure), and (*iv*) ecosystem processes (e.g., nutrient availability and primary productivity). Because of the large number of studies addressing the economic aspects (economic damage caused by the introduction of species), we included this topic as a fifth category.

We also grouped the studies according to three other issues (following Carrillo-Gavilán and Vilà 2010): invasiveness (invasive potential/reproduction and dispersal), invasibility (ecosystem attributes associated with susceptibility to colonisation and establishment of introduced species), both (invasiveness/invisibility) and impact (any change associated with the presence of invasive macrophytes). Finally, to identify any geographical bias in the studies on invasive macrophytes, we separated studies by country and geographic region (Palaearctic, Nearctic, Neotropical, Afrotropical, Australasian and Oriental).

Data analysis

We fit the total number of publications over the years with an exponential regression. To evaluate the progress of the scientific publications on the biological invasion using macrophytes, we compared the publications related to invasive macrophytes to all of the publications related to macrophytes in the same period. To accomplish this task, we used the Activity Index (*AI*): $AI=(CY/CT)/(TY/TT)$; where CY is the number of articles on invasive macrophytes published in a given year (y); CT is the total number of articles on invasive macrophytes published in all years; TY is the overall number of articles on macrophytes addressing topics other than invasion published in a given year (y); and TT is the overall number of articles on macrophytes addressing topics other than invasion published for all of the years studied. *AIs* have been used in several scientometric

evaluations (see Kumari 2006; Caliman et al. 2010; and references therein), and *AI* = 1 indicates that papers on invasive macrophytes were published at the same relative rate as those in the overall literature (in our case, articles with macrophytes that addressed topics other than invasion biology). *AI* > 1 indicates that invasive macrophytes articles were published at a higher relative frequency compared to the overall literature. *AI* < 1 indicates that invasive macrophyte articles were published at a relatively lower frequency compared to the overall literature. Because of the low number of papers in certain years, we analysed the *AI* using 5-year intervals. To estimate the *AI* values, we only used the articles published in the five journals in our survey with the highest number of publications. We used this criterion because publications on macrophytes were spread throughout 175 journals (see Results), and we preferred to be conservative and analyse the production of articles on invasive macrophytes according to the most important journals used by researchers in the field.

Results

The number of papers over time was explained with an exponential equation (R = 0.70; Figure 1A). However, the *AI* based on the five journals that published more papers on invasive macrophytes was highly variable and approached 1.0 between 2000 and 2013 (Figure 1B), indicating that the frequency of articles on biological invasion was similar to the frequency of articles focusing on other topics related to aquatic macrophytes. Values higher than 1.0 were found for 1990–2000 (Figure 1B).

The retrieved papers were published in 175 journals, and *Hydrobiologia*, *Aquatic Botany*, *Journal of Aquatic Plant Management*, *Biological Invasion* and *Freshwater Biology* were the most representative in terms of the number of publications on the subject, which consisted of 33.5% of the articles. The journals *Biological Invasions* and *Diversity and Distribution* represent the highest impact journals in the field of biological invasion, and they published only 4.8% and 0.4% of the assessed papers, respectively.

Of the 161 articles that were completely reviewed, 65 species of aquatic macrophytes were studied. The most frequently investigated species were *Myriophyllum spicatum* L. (41 articles), *Hydrilla verticillata* (L.f.) Royle (21 articles), *Phragmites australis* (Cav.) Steud. (16 articles), *Eicchornia crassipes* (Mart.) Solms-

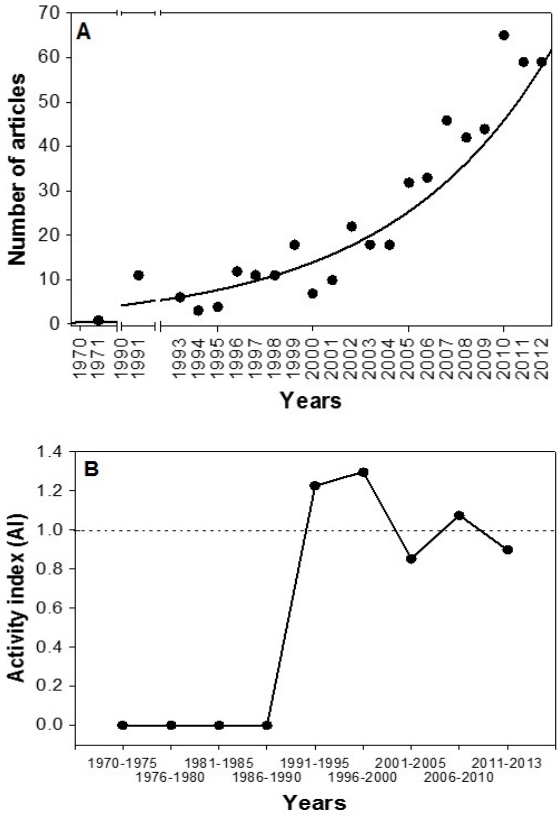

Figure 1. (A) Temporal trend in the number of papers published per year relating to the invasion of exotic and/or invasive aquatic plants. (B) Temporal trend of the activity index (AI) in research output that focuses on invasive macrophytes relative to all of the studies investigating aquatic macrophytes in the same period.

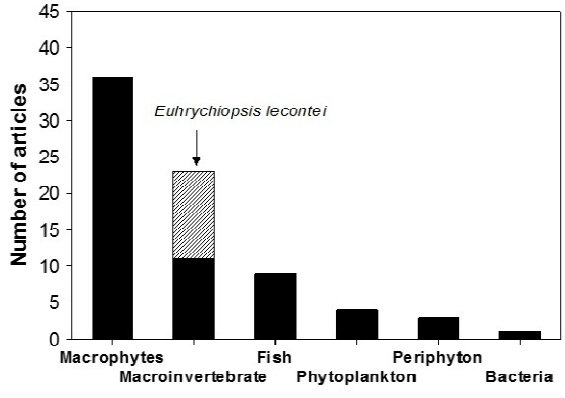

Figure 2. Taxonomic group or aquatic assemblage associated with invasive macrophytes. The gray area represents the number of articles that studied *E. lecontei*.

Laubach (13 articles) and *Elodea nuttallii* (Planchon) St. John (12 papers); these species represented 45.17% of the investigated species.

Regarding the taxonomic groups or assemblages associated with invasive macrophytes, native species of macrophytes received the most attention (36% of the studies), whereas zooplankton was the assemblage that received the least attention in the investigations (<1% of the total) (Figure 2). Phytoplankton, macro-invertebrates and fish were the subject of an intermediate number of studies (Figure 2). Among the macroinvertebrates, 36% of the investigations focused on Coleoptera *Euhrychiopsis lecontei* (Dietz), a native species to North America.

Regarding the type of study, experiments were the most representative and constituted 75.2% of the studies, which were grouped into laboratory/ greenhouse (58.7%) and *in situ* (41.3%). Studies using an observational approach accounted for 9.9% of the total, whereas theoretical studies (e.g., reviews and surveys) composed 3.1% of the total. Investigations employing a combination of two or more types of studies (experimental and observational) accounted for 11.8% of the total. Among the 161 articles, 50.2% considered the macrophytes both as exotic and invasive, 47.2% of the articles considered them as exotic, and 2.6% considered only native invasive macrophytes. Thus, our analysis relied mostly on non-native invasive species.

The results of assessing the level of organisation used in the investigations indicated that 28.9% of the investigations studied population dynamics (e.g., growth of invasive species), 23.9% employed an approach related to the community level (e.g., effects of invasive macrophytes on native diversity or vice-versa), 14.5% studied the economical aspect, 11.9% used an ecosystem perspective (e.g., productivity of invasive species and effects on environmental features) and 19.5% approached more than one level of organisation. Finally, studies of the genetics of these species were sparse and represented only 1.3% of the total.

Concerning the importance of plant traits or ecosystem properties related to invasions, 32.9% of all of the investigations were related to macrophyte invasiveness, 9.3% considered the invasibility of communities and 8.1% of the investigations studied both subjects simultaneously. Impacts were addressed in 24.2% of the studies. And 25.5% does not fit into the other categories.

Finally, 51% of the studies were conducted in the Nearctic region (77 investigations in the USA) and 25% were conducted in the Palearctic region (mainly in China and France, with 10 studies each). The Australasian region was investigated in 13% of the studies (Australia and New Zealand had 20 studies each) and the Afrotropical, Neo-tropical and Oriental regions were investigated in less than 10% of the studies each. Only one study was conducted in two countries belonging to two different biogeographic regions (USA and France).

Discussion

Our results demonstrated that there was a significant increase in the number of papers related to aquatic macrophyte invasions especially after the 1990's, and the number has increased more rapidly in the last decade. An increase in the ecological studies of aquatic macrophytes has been observed since the 1960's (Padial et al. 2008), but our data showed that the focus on invasive species has occurred only in the last 10 years, which is consistent with the field of invasion biology in general (Richardson and Pyšek 2008). The temporal trend confirms that biological invasions have attained a level of importance in general, which has also been observed by others (e.g., Qiu and Chen 2009; Puth and Post 2005; Gurevitch et al. 2011). However, invasive macrophytes have not seemed to receive more attention than other topics related to macrophytes after 2000 because the *AI* values have remained close to 1.0.

The journals with the highest impact in the biological invasion field (*Diversity and Distributions* and *Biological Invasions*) are not the sources most used by researchers who investigate macrophyte invasions. This finding may be related to the focus of these journals, which includes aquatic and terrestrial environments. Studies related to biological invasions are conducted more frequently in terrestrial ecosystems, which are the most visible and accessible habitats for humans, so they receive more attention from ecologists (Puth and Post 2005). In a general literature survey on invasive or exotic species for the period 1995–2004, 66.1% of all of the papers were concerned with terrestrial ecosystems with the remainder concerned with marine and freshwater ecosystems (Puth and Post 2005). However, the few studies in important journals in the field may also indicate that the investigations focusing on invasive macrophytes are not contributing to broader issues in the field of invasion biology, which occurs with terrestrial plants. The number

of studies in freshwater ecosystems testing the main hypotheses in the field of invasion biology is much lower than the number of studies conducted in terrestrial ecosystems (Jeschke et al. 2012), which corroborates the few studies concerning macrophytes that were published in leading journals of the field. Despite being under-utilised in the investigation of broader aspects of invasion biology, macrophytes can be considered an appropriate means of connecting to the issues in this field because they are key elements in waterscapes (Wetzel 2001), and invasive macrophytes can cause serious ecological and economic damage worldwide (e.g., Pieterse and Murphy 1990).

The high percentage of research found in our study that involved experimental approaches should be noted because observational studies generally outweigh experimental studies in the field of limnology (Bourget and Fortin 1995). The high number of experimental investigations compared to observational investigations suggests that research on macrophyte invasions is mainly designed to determine the processes and mechanisms behind invasions. We noted that the majority of experiments attempt to understand the invasiveness and impacts, which are appropriate fields to be investigated through an experimental approach. In this sense, our survey differs from studies that focus on aquatic invasive species in general, which usually record a higher percentage of studies using an observational approach compared to an experimental approach (Olyarnik et al. 2008). Although we recognise the importance of experiments for determining mechanisms associated with invasions, the few investigations conducted under more realistic and applied situations (*in situ*) is a gap that should be fulfilled because these investigations complement experiments conducted under more controlled conditions.

According to our expectations, the current knowledge of macrophyte impacts is restricted to certain exotic dominant species because of their high invasion potential (e.g., *M. spicatum*, *P. australis*, *H. verticillata*, *E. nuttallii* and *E. canadensis*) (Hershner and Havens 2008; Sousa et al. 2010). Furthermore, these species mainly invade more developed temperate countries and subtropical zones and demonstrate the need for a larger number of investigations in tropical ecosystems. For example, the macrophyte *M. spicatum* was the most frequently studied, and it is considered invasive in most of the world, but especially in the United States. In addition, *M. spicatum* can inhabit a variety of aquatic ecosystems, such as lakes, ponds, rivers and irrigation canals (Eiswerth et al. 2000). However, *E. crassipes*, which is among the 100 major weeds in the world (IUCN 2000), was the fourth most studied species. Other free-floating species such as *S. molesta* and *P. stratiotes* are highly invasive in the tropics (Coetzee et al. 2011) but have been poorly studied. The gap between the high invasive potential and low number of studies on these free-floating species can be attributed to the fact that they primarily invade warmer regions where financial resources and hence studies are scarce.

Macroinvertebrates is the second group most studied, the preference for studying macroinvertebrates may be a result of the influence macrophytes have on their colonisation, predation, distribution, trophic relationships and food availability (van der Berg et al. 1997). Moreover, the ease of studying macroinvertebrate organisms compared to other organisms, such as fish or microscopic organisms, may partially explain this preference. In general, the analysed studies assessed the distribution, abundance and species richness of macroinvertebrates when coupled with exotic species of aquatic macrophytes. In particular, the Coleoptera *E. lecontei* (Dietz) was the most studied species, and it is directly associated with research on the species *M. spicatum* because *E. lecontei* can be used in the biological control of *M. spicatum* (Sheldon and Creed 1995; Lambrinos 2004).

According to our records, studies investigating plankton and fish associated with invasive macrophytes within ecosystems are poorly represented. This gap relating invasive macrophytes with fish is surprising because macrophytes have an important role in fish communities (Gomes et al. 2012). In addition, associated fish have a known role in economic aspects, relating to recreational and commercial fishing (Hoeinghaus et al. 2009) and may affect ecosystem structure and functioning (Pendleton et al. 2014). Thus, changes to fish stocks caused by invasive macrophytes may impact economic and ecological aspects. Even more surprising was the lack of studies associating the role of macrophyte invasions on microorganisms (bacteria and fungi) and vice-versa. For example, studies have shown that mycorrhizae play a key role in terrestrial plant invasions (Pringle and Wolfe 2011) and mycorrhizae are also associated with macrophytes (Beck-Nielsen and Madsen 2001); however, the links between invasive macrophytes and fungi have apparently been ignored.

Most of the investigated studies have considered macrophytes as both exotic and invasive species,

which is most likely because a majority of invasive species overcome dispersal barriers to their establishment and spread to new regions where they proliferate and are considered exotic (Ricciardi and Cohen 2007). The major concern with proportionate invasions by exotic species stems from the ability of these species to reduce the diversity of native species (Richardson et al. 2000; Wilson and Ricciardi 2009), compete with other macrophyte species (Mony et al. 2007; Sousa et al. 2009) and change the composition of other aquatic communities (e.g., Douglas and O'Connor 2003; Wilson and Ricciardi 2009; Casatti et al. 2009).

Studies conducted at the population and community level dominated our dataset, but ecosystems were less studied. This organisational level should be investigated more frequently because the overall impacts to ecosystems are not readily detected and sometimes remain undetecteded (Simberloff et al. 2013). In addition, entire ecosystems may change in response to invasions (Yarrow et al. 2009; Strayer 2010). Studies employing more than one level of organisation were also underrepresented. This trend parallels the trends of terrestrial ecosystems in which studies concerning the impact of invasive plants on different trophic levels are scarce (Pyšek et al. 2012).

When considering the invasiveness of macrophytes compared to the invasibility of ecosystems, the former has received more attention, showing that the study of attributes related to macrophyte species that facilitate invasion is preferred by aquatic investigators studying macrophytes. Our data set also showed that few investigations addressed invasiveness and invasibility together (8.07%), and the results were less than those found for terrestrial invasive plants (13.5%, according to Peternon and Pivelli 2006). Thus, our results highlight that additional knowledge on the environmental factors that affect invasions by macrophytes and studies that address both invasiveness and invasibility are still required. Studies that address both invasiveness and invasibility are becoming increasingly common in invasion biology (Richardson and Pyšek 2006; Thuiller et al. 2010) because the analysis of these two factors can result in an improved understanding and ability to predict the spread and impact of invasive species, which are the primary topics of applied ecology. Hypotheses that combine invader-ecosystem interactions have a greater potential to improve the knowledge of invasions than separate studies of invaders or habitat features (Jeschke et al. 2012).

Finally, our study also showed a clear geographical bias in the studies of invasive macrophytes, which are more frequent in the Nearctic (nearly half of all studies are conducted in the USA) and Palearctic regions. The same bias occurs in the field of biological invasion in general (Qiu and Chen 2009), and it may limit a better understanding of invasions because tropical and more diverse regions are investigated less frequently (Fridley et al. 2007; Pyšek et al. 2008). The lack of studies developed simultaneously in two different biogeographic regions is also a gap that should be addressed because the combination of results from native and invaded ranges contributes to a better understanding of the mechanisms that regulate invasion success (e.g., Thiébaut 2011).

In summary, our study shows that there is a diverse array of topics covered in the studies of invasive macrophytes, but there is a lack of integration between topics, meaning that invasive species and the environments that are invaded are analysed separately. This can limit the available information on the ecology and impacts of invasive macrophytes. Thus, the effects of invasive species on native communities and ecosystem dynamics (e.g., primary productivity, nutrient cycling, etc.), susceptibility of native ecosystems to invasion by non-native species, and predictability of potentially invasive species may be misunderstood. Moreover, studies with invasive macrophytes are rare in the leading journals of the biological invasion field, indicating that these plants are seldom used to test more general theories in the field. Finally, few articles have focused on important invaders in the tropics, fish-macrophyte and microorganism-macrophyte interactions, genetics and the impact of invasive macrophytes on more than one level of organisation. These are important and necessary issues for conservation, and they are areas that should receive a greater degree of emphasis in future research on invasive macrophytes.

Acknowledgements

H.B.A.E. acknowledges the National Council for Scientific and Technological Development (CNPq) for providing a scholarship, and S.M.T. is especially thankful to the CNPq for their continuous funding through a Research Productivity Grant. C.A.U. would like to thank FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo - Process nº 2012/21517-9). We would also like to thank the two anonymous reviewers whose comments improved the first draft of this paper.

References

Balian EV, Segers H, Lévêque C, Martens K (2008) The freshwater animal diversity assessment: an overview of the results. *Hydrobiologia* 595: 627–637, http://dx.doi.org/10.1007/s10750-007-9246-3

Beck-Nielsen D, Madsen TV (2001) Occurrence of vesicular-arbuscular mycorrhiza in aquatic macrophytes from lakes and streams. *Aquatic Botany* 71: 141–148, http://dx.doi.org/10.1016/S0304-3770(01)00180-2

Bourget E, Fortin MJ (1995) A commentary on current approaches in the aquatic sciences. In: Space Partition within Aquatic Ecosystems. Springer Netherlands, pp 1–16, http://dx.doi.org/10.1007/978-94-011-0293-3_1

Caliman A, Pires AF, Esteves FA, Bozelli RL, Farjalla VF (2010) The prominence of and biases in biodiversity and ecosystem functioning research. *Biodiversity and Conservation* 19: 651–664, http://dx.doi.org/10.1007/s10531-009-9725-0

Capers RS, Selsky R, Bugbee GJ, White JC (2007) Aquatic plant community invasibility and scale-dependent patterns in native and invasive species richness. *Ecology* 88: 3135–3143, http://dx.doi.org/10.1890/06-1911.1

Carrillo-Gavilán MA, Vilà M (2010) Little evidence of invasion by alien conifers in Europe. *Diversity and Distributions* 16: 203–213, http://dx.doi.org/10.1111/j.1472-4642.2010.00648.x

Casatti L, de Paula Ferreira C, Carvalho FR (2009) Grass-dominated stream sites exhibit low fish species diversity and dominance by guppies: an assessment of two tropical pasture river basins. *Hydrobiologia* 632: 273–283, http://dx.doi.org/10.1007/s10750-009-9849-y

Coetzee JA, Hill MP, Byrne MJ, Bownes A (2011) A Review of the Biological Control Programmes on *Eichhornia crassipes* (C.Mart.) Solms (Pontederiaceae), *Salvinia molesta* D. S. Mitch. (Salviniaceae), *Pistia stratiotes* L. (Araceae), *Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae) and *Azolla filiculoides* Lam. (Azollaceae) in South Africa. *African Entomology* 19: 451–468, http://dx.doi.org/10.4001/003.019.0202

Davis ME (2000) Invasion Biology. Oxford University Press Inc., New York, 259 pp

Douglas MM, O'Connor RA (2003) Effects of the exotic macrophyte, para grass (*Urochloa mutica*), on benthic and epiphytic macroinvertebrates of a tropical floodplain. *Freshwater Biology* 48: 962–971, http://dx.doi.org/10.1046/j.1365-2427.2003.01072.x

Eiswerth ME, Donaldson SG, Johnson WS (2000) Potential environmental impacts and economic damages of Eurasian Watermilfoil (*Myriophyllum spicatum*) in Western Nevada and Northeastern California. *Weed Technology* 14: 511–518, http://dx.doi.org/10.1614/0890-037X(2000)014[0511:PEIAED]2.0.CO;2

Engelhardt KA (2011) Eutrophication aquatic. In: Simberloff D, Rejmánek M (eds), Encyclopedia of biological invasions. University of California Press, Berkeley, USA, pp 209–213

Fridley JD, Stachowicz JJ, Naeem S, Sax DF, Seabloom EW, Smith MD, Stohlgren TJ, Tilman D, Von Holle B (2007) The invasion paradox: reconciling pattern and process in species invasions. *Ecology* 88: 3–17, http://dx.doi.org/10.1890/0012-9658(2007)88[3:TIPRPA]2.0.CO;2

Gherardi F (2007) Understanding the impact of invasive crayfish. In: Biological invaders in inland waters: Profiles, distribution, and threats. Springer Netherlands, pp 501–542

Gomes LC, Bulla K, Agostinho AA, Vasconcelos LP, Miranda LE (2012) Fish assemblage dynamics in a Neotropical floodplain relative to aquatic macrophytes and the homogenizing effect of a flood pulse. *Hydrobiologia* 685: 97–101, http://dx.doi.org/10.1007/s10750-011-0870-6

Gurevitch J, Fox GA, Wardle GM, Taub D (2011) Emergent insights from the synthesis of conceptual framework for biological invasions. *Ecology Letters* 14: 407–418, http://dx.doi.org/10.1111/j.1461-0248.2011.01594.x

Hershner C, Havens KJ (2008) Managing invasive aquatic plants in a changing system: strategic consideration of ecosystem services. *Conservation Biology* 22: 544–550, http://dx.doi.org/10.1111/j.1523-1739.2008.00957.x

Hoeinghaus DJ, Agostinho AA, Gomes LC, Pelicice FM, Okada EK, Latini JD, Kashiwaqui EAL, Winemiller KO (2009) Effects of River Impoundment on Ecosystem Services of Large Tropical Rivers: Embodied Energy and Market Value of Artisanal Fisheries. *Conservation Biology* 23: 1222–1231, http://dx.doi.org/10.1111/j.1523-1739.2009.01248.x

Hummel RL, Walgenback JF, Hoyt GD, Kennedy GG (2002) Effects of production system on vegetable arthropods and their natural enemies. *Agriculture Ecosystems and Environment* 93: 165–176, http://dx.doi.org/10.1016/S0167-8809(01)00345-0

IUCN Species Survival Commission (2000) "IUCN Red List of threatened species."World Conservation Union, Gland, Switzerland (http://www.redlist.org)

Jenkins M (2003) Prospects for biodiversity. *Science* 302: 1175–1177, http://dx.doi.org/10.1126/science.1088666

Jeschke J, Aparicio LG, Haider S, Heger T, Lortie C, Pyšek P, Strayer D (2012) Support for major hypotheses in invasion biology is uneven and declining. *NeoBiota* 14: 1–20, http://dx.doi.org/10.3897/neobiota.14.3435

Johnson PTJ, Olden JD, Solomon CT, Zanden MJV (2009) Interactions among invaders: community and ecosystem effects of multiple invasive species in an experimental aquatic system. *Oecologia* 159: 161–170, http://dx.doi.org/10.1007/s00442-008-1176-x

Kumari L (2006) Trends in synthetic organic chemistry research. Cross-country comparison of activity index. *Scientometrics* 67: 467–476, http://dx.doi.org/10.1556/Scient.67.2006.3.8

Lambrinos JG (2004) How interactions between ecology and evolution influence contemporary invasion dynamics. *Ecology* 85: 2061–2070, http://dx.doi.org/10.1890/03-8013

Madsen JD, Sutherland JW, Bloomfield JA, Eichler LW, Boylen CW (1991) The decline of native vegetation under dense Eurasian watermilfoil canopies. *Journal of Aquatic Plant and Management* 29: 94–99

Matlack GR, Schaub JR (2011) Long–term persistence and spatial assortment of nonnative plant species in second-growth forests. *Ecography* 34(4): 649–658, http://dx.doi.org/10.1111/j.1600-0587.2010.06654.x

Mony C, Koschnick TJ, Haller WT, Muller S (2007) Competition between two invasive Hydrocharitaceae (*Hydrilla verticillata* (Lf) (Royle) and *Egeria densa* (Planch)) as influenced by sediment fertility and season. *Aquatic Botany* 86: 236–242, http://dx.doi.org/10.1016/j.aquabot.2006.11.007

Olyarnik SV, Bracken MES, Byrnes JE, Hughes AR, Hultgren KM, Stachowicz JJ (2008) Ecological factors affecting community invisibility. In: Rilov G, Crooks JA (eds), Biological invasions of marine ecosystems: ecological, management and geographic perspectives. Springer, Heidelberg, Germany, pp 587–617

Padial AA, Bini LM, Thomaz SM (2008) The study of aquatic macrophytes in Neotropics: a scientometrical view of the main trends and gaps. *Brazilian Journal of Biology* 68: 1051–1059, http://dx.doi.org/10.1590/S1519-69842008000500012

Parker IM, Simberloff D, Lonsdale WM, Goodell K, Wonham M, Kareiva PM, Goldwasser L (1999) Impact: toward a framework for understanding the ecological effects of invaders. *Biological Invasions* 1: 3–19, http://dx.doi.org/10.1023/A:1010034312781

Pendleton RM, Hoeinghaus DJ, Gomes LC, Agostinho AA (2014) Loss of rare fish species from tropical floodplain food webs affects community structure and ecosystem multifunctionality in a mesocosm experiment. *PloS ONE* 9(1): e84568, http://dx.doi.org/10.1371/journal.pone.0084568

Peternon D, Pivello VR (2006) Plantas invasoras: representatividade da pesquisa dos países tropicais no contexto mundial. *Natureza and Conservação* 6: 65–77

Pieterse AH, Murphy KJ (1990) Aquatic weeds: the ecology and management nuisance aquatic vegetation. Oxford University Press, Oxford, 612 pp

Pringle A, Wolfe B (2011) Mycorrhizae. In: Simberloff D, Rejmánek M (eds), Encyclopedia of biological invasions. University of California Press, Berkeley, USA, pp 468–471

Puth LM, Post DM (2005) Studying invasion: have we missed the boat? *Ecology Letters* 8: 715–721, http://dx.doi.org/10.1111/j.1461-0248.2005.00774.x

Pyšek P, Richardson DM (2006) The biogeography of naturalization in alien plants. *Journal of Biogeography* 33: 2040–2050, http://dx.doi.org/10.1111/j.1365-2699.2006.01578.x

Pyšek P, Richardson DM, Pergl J, Jarošík V, Sixtová Z, Weber E (2008) Geografical and taxonomic biases in invasion ecology. *Trends in Ecology & Evolution* 23: 237–244, http://dx.doi.org/10.1016/j.tree.2008.02.002

Pyšek P, Jarošík V, Hulme PE, Pergl J, Hejda M, Schaffner U, Vilà M (2012) A global assessment of invasive plant impacts on resident species, communities and ecosystems: the interaction of impact measures, invading species' traits and environment. *Global Change Biology* 18: 1725–1737, http://dx.doi.org/10.1111/j.1365-2486.2011.02636.x

Qiu H, Chen Y (2009) Bibliometric analysis of biological invasions research during the period of 1991 to 2007. *Scientometrics* 3: 601–610, http://dx.doi.org/10.1007/s11192-008-2207-4

Ricciardi A, Cohen J (2007) The invasiveness of an introduced species does not predict its impact. *Biological Invasions* 9: 309–315, http://dx.doi.org/10.1007/s10530-006-9034-4

Richardson DM, Allsopp N, D'Antonio CM, Milton SJ, Rejmanek M (2000) Plant invasions—the role of mutualisms. *Biological Reviews* 75: 65–93, http://dx.doi.org/10.1017/S0006323199005435

Richardson DM, Pyšek P (2006) Plant invasions: merging the concepts of species invasiveness and community invisibility. *Progress in Physical Geography* 30: 409–431, http://dx.doi.org/10.1191/0309133306pp490pr

Richardson DM, Pyšek P (2008) Fifty years of invasion ecology–the legacy of Charles Elton. *Diversity and Distributions* 14: 161–168, http://dx.doi.org/10.1111/j.1472-4642.2007.00464.x

Sala OE, Chapin FS, Armesto JJ, Berlow E, Bloomfield J, Dirzo R, Wall DH (2000) Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774, http://dx.doi.org/10.1126/science.287.5459.1770

Santamaria L (2002) Why are most aquatic plants widely distributed? Dispersal, clonal growth and small-scale heterogeneity in a stressful environment. *Acta Oecologica* 23: 137–154, http://dx.doi.org/10.1016/S1146-609X(02)01146-3

Sheldon SP, Creed RP (1995) Use of native insect as a biocontrol for an introduced weed. *Ecological Applications* 5: 1122–1132, http://dx.doi.org/10.2307/2269359

Simberloff D, Martin JL, Genovesi P, Maris V, Wardle DA, Aronson J, Courchamp F, Galil B, García-Berthou E, Pascal M, Pyšek P, Sousa R, Tabacchi E, Vilá M (2013) Impacts of biological invasions: what's what and the way forward. *Trends in Ecology & Evolution* 28: 58–66, http://dx.doi.org/10.1016/j.tree.2012.07.013

Sousa WTZ, Thomaz SM, Murphy, KJ, Silveira MJ, Mormul RP (2009) Environmental predictors of the occurrence of exotic *Hydrilla verticillata* (Lf) Royle and native *Egeria najas* Planch. in a sub-tropical river floodplain: the Upper River Paraná, Brazil. *Hydrobiologia* 632: 65–78, http://dx.doi.org/10.1007/s10750-009-9828-3

Sousa WTZ, Thomaz SM, Murphy KJ (2010) Response of native *Egeria najas* Planch. and invasive *Hydrilla verticillata* (L.f.) Royle to altered hydroecological regime in a subtropical river. *Aquatic Botany* 92: 40–48, http://dx.doi.org/10.1016/j.aquabot.2009.10.002

Steedman RJ, Whillans TH, Behnm AP, Bray KE, Cullis KI, Holland MM, Stoddart SJ, White RJ (1996) Use of historical information for conservation and restoration of Great Lakes aquatic habitat. *Canadian Journal of Fisheries and Aquatic Sciences* 53: 415–423, http://dx.doi.org/10.1139/f96-017

Strayer DL (2010) Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. *Freshwater Biology* 55: 152–174, http://dx.doi.org/10.1111/j.1365-2427.2009.02380.x

Taniguchi H, Nakano S, Tokeshi M (2003) Influences of habitat complexity on the diversity and abundance of epiphytic invertebrates on plants. *Freshwater Biology* 48: 718–728, http://dx.doi.org/10.1046/j.1365-2427.2003.01047.x

Theel HJ, Dibble ED, Madsen JD (2008) Differential influence of a monotypic and diverse native aquatic plant bed on a macroinvertebrate assemblage; an experimental implication of exotic plant induced habitat. *Hydrobiologia* 600: 77–87, http://dx.doi.org/10.1007/s10750-007-9177-z

Thiébaut G (2011) Invasion success of non-indigenous aquatic and semi-aquatic plants in their native and introduced ranges. A comparison between their invasiveness in North America and in France. *Biological Invasion* 9: 1–12, http://dx.doi.org/10.1007/s10530-006-9000-1

Thuiller W, Gallien L, Boulangeat I, De Bello F, Münkemüller T, Roquet C, Lavergne S (2010) Resolving Darwin's naturalization conundrum: a quest for evidence. *Diversity and Distributions* 16: 461–475, http://dx.doi.org/10.1111/j.1472-4642.2010.00645.x

van der Berg MS, Coops H, Noordhuis R, van Schie J, Simons J (1997) Macroinvertebrate communities in relation to submerged vegetation in two *Chara*-dominated lakes. *Hydrobiologia* 342: 143–150, http://dx.doi.org/10.1023/A:1017094013491

Wetzel RG (2001) Limnology: Lake and river ecosystems. Academic Press, San Diego, 1006 pp

Wilson SJ, Ricciardi A (2009) Epiphytic macroinvertebrate communities on Eurasian watermilfoil (*Myriophyllum spicatum*) and native milfoils *Myriophyllum sibericum* and *Myriophyllum alterniflorum* in eastern North America. *Canadian Journal of Fisheries and Aquatic Sciences* 66(1): 18–30, http://dx.doi.org/10.1139/F08-187

Yarrow M, Marín VH, Finlayson M, Tironi A, Delgado LE, Fischer F (2009) The ecology of *Egeria densa* Planchon (Liliopsida: Alismatales): A wetland ecosystem engineer? *Revista Chilena de Historia Natural* 82: 299–313

The following supplementary material is available for this article:

Appendix 1. List of papers and information retained for analysis.

This material is available as part of online article from: http://www.aquaticinvasions.net/2014/Supplements/AI_2014_Evangelista_etal_Supplement.xls