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Advancing research on alien species and biological invasions

Insights into invasion and restoration ecology: Time to collaborate towards a holistic approach to tackle biological invasions

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Abstract

The aim of our study is to provide an integrated framework for the management of alien plant invasions, combining insights and experiences from the fields of invasion and restoration ecology to enable more effective management of invasive species. To determine linkages between the scientific outputs of the two disciplines we used an existing data base on restoration studies between 2000 and 2008 and did a bibliometric analysis. We identified the type of restoration applied, determined by the aim of the study, and conducted a content analysis on 208 selected studies with a link to biological invasions (invasion-restoration studies). We found a total of 1075 articles on ecosystem restoration, with only eight percent of the studies having the main objective to control alien invasions. The content analysis of 208 invasion-restoration studies showed that the majority of the studies focused on causes of degradation other than alien invasions. If invaders were referred to as the main driver of degradation, the prevalent cause for degradation was invaders outcompeting and replacing native species. Mechanical control of alien plant invasions was by far the most common control method used. Measures that went beyond the removal of alien plants were implemented in sixty-five percent of the studies.

Although invasion control was not as common as other types of restoration, a closer look at the sub-group of invasion-restoration studies shows a clear link between restoration and invasion ecology. Concerns, as identified in the literature review, are firstly that restoration activities mostly focus on controlling the invader while other underlying causes for degradation are neglected, and secondly that the current approach of dealing with alien invasions lacks a combination of theoretical and practical aspects.

We suggest that closer collaboration between invasion and restoration ecologists can help to improve the management of alien plant invasions. We conclude with a framework and a case study from Perth Western Australia integrating the two disciplines, with the aim of informing restoration practice.

Keywords

Adaptive management, disturbance, ecosystem function, exotic plants, knowledge-doing gap, rehabilitation

Introduction

Management of invaded ecosystems is an increasingly complex problem worldwide (e.g. Roura-Pascual et al. 2009). It has been acknowledged that clearing of invasive species alone is often not sufficient for re-establishing native communities; therefore some form of restoration is increasingly seen as vital when dealing with alien invasions (Esler et al. 2008). However, restoration efforts are challenged by numerous obstacles caused by invasive species such as altered ecosystem properties and ecosystem functions. Consequently, restoration efforts often have unexpected outcomes or even unforeseen negative consequences (Zavaleta et al. 2001).

In this study we attempt to find ways of improving the management of alien plant invasions by combining insights and experiences from the fields of invasion and restoration ecology with the aim of informing restoration practice. To tackle the challenge of combining efforts from both fields we first need to understand whether, how and where the two disciplines overlap in terms of applied management. We therefore begin our study with a literature analysis looking at restoration studies with a link to biological invasions. Building on the findings of our literature analysis we provide an integrated framework for the management of alien plant invasions. We focus on plant invasions only as these represent the primary challenge in terrestrial restoration ecology.

Restoration ecology and invasion ecology can be seen as synergistic disciplines with many similarities and cross cutting debates. They both originated in the mid -20th century and are considered relatively new disciplines in the field of ecology. Both are applied, focusing on conservation and management issues (Hobbs and Richardson 2011) but not without controversy (Vince et al. 2011, Davis et al. 2011, Lambertini et al. 2011, Simberloff et al. 2011).

Dealing with invasive alien species is one of the key elements for ecosystem restoration (D'Antonio and Meyerson 2002). The removal of invasive alien species is often conducted to achieve goals other than just the control of the invader (e.g., to improve ecosystem function and/or services or conserve or reduce biodiversity loss) however, more and more restoration projects define the removal of alien species as a goal in itself (Hobbs and Richardson 2011).

Invasion ecologists have been criticised for being detached from the practicalities of dealing with invasive species management (Richardson et al. 2004, Shaw et al. 2010) and for making little progress in reducing negative impacts of invasions (Hulme 2003) while restoration ecology has been criticised for focusing too much on the symptoms of ecosystem degradation (e.g., controlling the invader without manipulating abiotic and biotic ecosystem components), thereby neglecting to consider the causes for ecosystem damage (Buckley 2008), which in some cases resulted in wrong assumptions and ineffective approaches (Hobbs and Richardson 2011).

In summary, restoration ecology and invasion ecology can be described as synergistic disciplines which share similarities but also differ in aspects and which both have been criticised for certain shortcomings. We therefore suggest that a combined effort between invasion and restoration ecologists of sharing and interpreting knowledge, conducting research and applying the results to management and restoration of ecosystems could improve our understanding of biological invasions. We further suggest that understandings from invasion ecology could inform restoration activities to increase their effectiveness while reducing the impacts of invasive species leading to more resilient restored ecosystems. The "perfect world" scenario would be if invasion ecology could provide insights incorporating theoretical knowledge into management scenarios, while delivering information on the causes and consequences of ecosystem degradation. On the other hand restoration ecology could (on the basis of these insights) deliver more effective solutions to these problems, while embedding the work in a stronger theoretical context.

To elucidate the link between restoration and invasion ecology and to provide a basis for our framework, we ask the overarching questions: To what extent is the link between restoration and invasion ecology reflected in the scientific literature? What role do biological invasions play in ecosystem degradation, how do they influence the success of restoration activities and how can restoration benefit the management of alien plant invasions?

More specific questions are:

1. How many restoration studies published between 2000 and 2008 have invasion control as an explicit aim and how do these studies rank in comparison to other types of restoration (i.e. forest restoration or wetland restoration)?
2. How many restoration studies have a link to biological invasions (from hereon referred to as invasion-restoration studies) and is there a primary geographic focus (country and ecosystem) of invasion-restoration studies?
3. How many invasion-restoration studies investigate the outcomes of restoration projects conducted by practitioners and how many studies give recommendations for restoration? If recommendations are given, were these accounted for in restoration actions?
4. How many studies investigate invasive species as a main driver of degradation (causes for degradation) and, if invasive species are only symptoms of degradation, which other drivers have been identified?
5. If invaders are referred to as only cause for degradation, which negative effects are viewed as responsible for the degradation (e.g. nutrient enrichment, competition for resources)?

6. Which percentage of the invasion-restoration studies have invasion control as an explicit aim and what is the adopted approach for remedy (invasion control measure, e.g. herbicide application and burning)?
7. Which percentage of studies implement measures that go beyond the removal of alien plants, what are the reasons for taking additional steps and do studies report long term success?
8. If the study has other objectives (e.g. forest restoration) and invasion control is not the explicit aim, how do invaders influence the success of restoration activities?

Based on the results of our literature analysis, we identify general concerns and methodological gaps. We then develop a framework incorporating ecosystem interactions and invasive species into restoration planning and goal setting. To illustrate the relevance of our framework we conclude with a case study utilising the framework in restoration projects in the Canning River, Perth, south-western Australia.

Methods

Terminology followed Pyšek et al. (2004), referring to an alien as "a plant taxa in a given area whose presence there is due to intentional or accidental introduction as a result of human activities" and to invasive as "naturalized plants that produce reproductive offspring, often in very large numbers, at considerable distances from parent plants, and thus have the potential to spread over a considerable area". As synonyms for the term alien we identified exotics, non-native species, introduced species and non-indigenous species. The term restoration is used following the definition of the Society for Ecological Restoration (SER 2004) as "the process of assisting the recovery of an ecosystem that has been degraded damaged or destroyed" and as a synonym we identified rehabilitation.

For the literature search we used two different sources. Firstly, we used an existing data base on restoration studies for the years 2000 - 2008 (for more details see Aronson et al. 2010). Secondly we searched the ISI web of science for papers using the term invasion and its derivates, excluding conference proceedings, refined the results with ecology as "subject area" and searched for restoration and rehabilitation. We then defined 17 key journals in invasion ecology (Pyšek et al. 2006) and restricted our analysis to these journals (Appendix S1). We excluded "grey literature" although we are well aware that many restoration studies are only published in the form of reports or popular articles and acknowledge that this is a shortcoming of our study.

We found a total of 1075 articles on ecosystem restoration that included (but were not limited to) those linked in some way to alien invasion. Analysing these papers, we identified the type of restoration with 10 different restoration types ranging from forest and wetland restoration to restoration after alien invasion. We determined the type of restoration by the main aim of the study, which means that for example a restoration project taking place in a wetland which is invaded by alien species with the aim of controlling the invader was classified as "restoration after alien invasion" (Appendix S2).

Second, we selected all restoration studies with a link to biological invasions on the basis of the presence of key terms and their combinations occurring in title, keywords and abstract. The resulting 208 studies are from here-on referred to as invasion-restoration studies and include all studies that mention biological invasions; hence they include (but are not limited to) studies that are aiming to control the invader. We conducted a content analysis (Babbie and Mouton 2001) of the 208 articles: The latent content or underlying meaning of the articles was coded by reading each article and making an assessment of its overall emphasis according to a predetermined list of variables (Appendix S3). The variables were selected to examine the current practise of tackling alien invasions. We selected criteria to identify the objective and geographic focus of the study, the adopted approach for remedy (restoration approach and invasion control measures), and the reason for intervention (causes of degradation).

Results

The importance of invasion control for restoration studies

We examined 1075 restoration studies in 62 countries. An overall comparison showed that the aim 'invasion control' globally ranks fourth (90 studies, 8 %) after forest, wetland, and species restoration. Except for Europe, all continents have a clear bias towards forest restoration. Africa is the only continent on which invasion control ranges second after forest restoration with 16 % of the restoration studies having the main objective to control alien invasions. In Asia and Central America forest restoration plays by far the most important role (40 % and 68 % of all studies), whereas no study on invasion control was recorded in our database. In North America and South America invasion control ranges third (12 % and 8 % respectively) after forest restoration and wetland restoration. For Central America no study on invasion control was recorded in our data base. In Europe invasion control was only included in three percent of the studies. In Oceania (New Zealand, Australia and Hawaii) invasion control ranks fifth (8 %) (Figure 1).

Invasion-restoration studies characterised

Of the 1075 studies investigated 208 (19 %) had a link to biological invasions (invasion-restoration studies). More than 50 % of all invasion-restoration studies have been conducted in the USA (134 studies). The other 50 % have been conducted in Europe (27 studies), Australia (14 studies) and Canada (11 studies). Africa and South America are only represented in six and three studies respectively. Thirty percent of the studies focus on grassland ecosystems, 16 % on forest ecosystems and 14 % on wetlands.

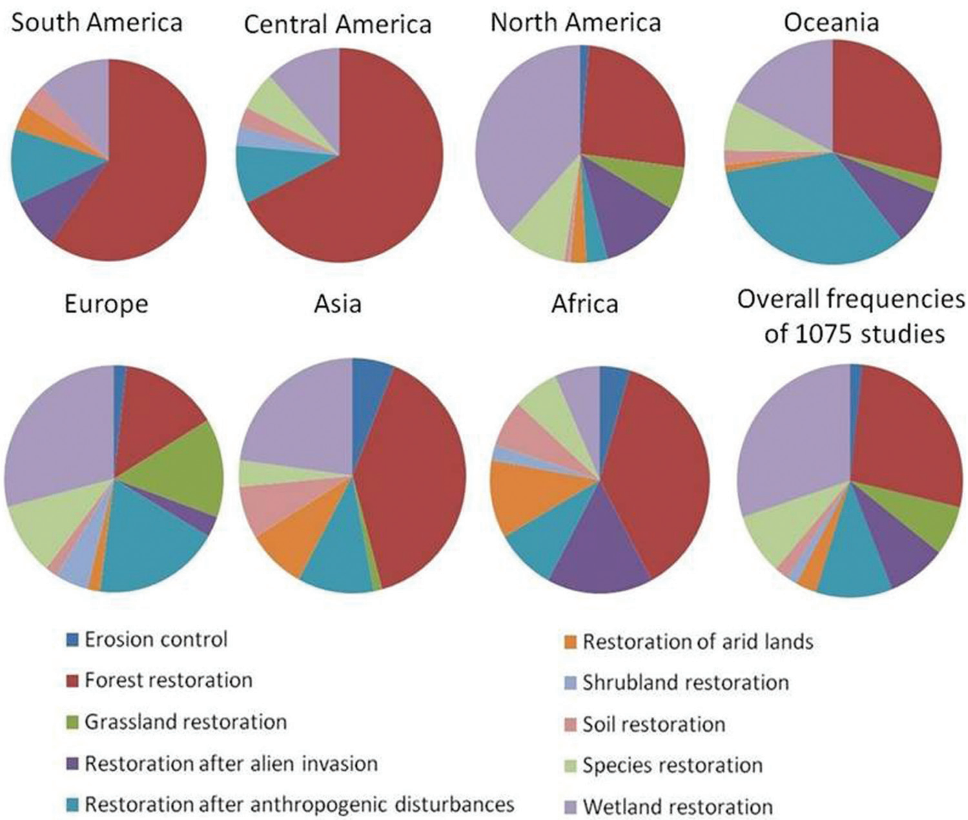

Figure 1. Types of restoration in different geographic regions of the world. Restoration types in different geographical regions identified in a literature analysis of 1075 restoration studies.

Other ecosystems under study are shrublands (8 %), woodlands and savanna (18 %) and human modified ecosystems (7 %) (Figure 2a).

Seventy-six percent (158 studies) of the invasion-restoration studies were empirical studies including restoration experiments but also other experiments (e.g. competition or impact studies). The results below refer to the empirical studies.

Thirteen percent of the empirical studies investigated outcomes of restoration projects conducted by practitioners (compared to pure scientific restoration experiments) and several studies did provide recommendations for restoration, however, only one study reported on scientific results that were directly translated into restoration actions.

Thirty-two percent of the empirical studies referred to alien invasion as main cause for degradation whereas 52 % of the studies referred to alien invasions as a symptom of degradation. Other prevalent causes for degradation were overgrazing and agricultural activities (each 32 %), deforestation (12 %), overexploitation of vegetation (8 %) and industrial activities (9 %) (Figure 2b). Invasive native species were the subject of ten percent of the studies with four studies referring to native invasions as cause for degradation and 16 studies referring to native invasions as symptom of degradation.

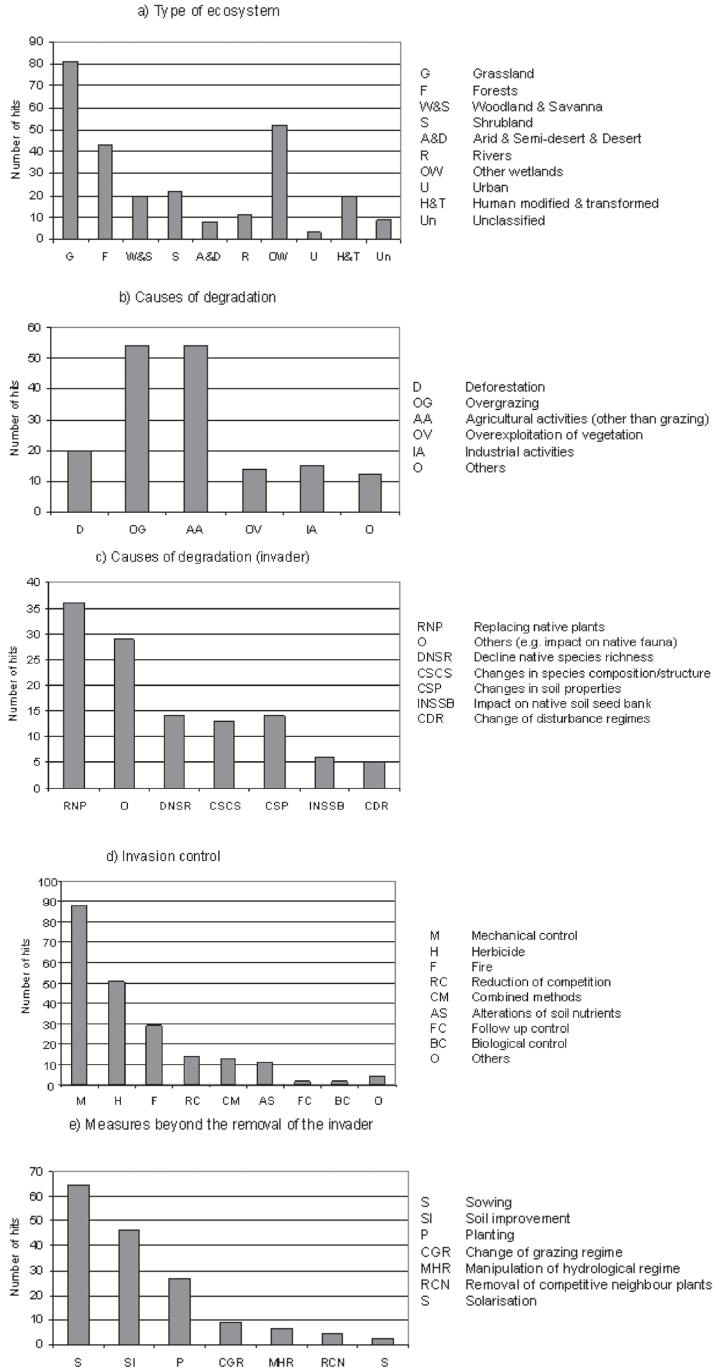

Figure 2. Restoration studies with a linkage to biological invasion (invasion-restoration studies) in different categories. **a** Ecosystem types **b** causes of degradation **c** causes of degradation by the invader **d** measures of invasion control and **e** measures adopted beyond the removal of the invader as reflected in a literature review of 208 publications with a link to biological invasions (invasion-restoration studies).

If invaders were referred to as the main driver of degradation, the prevalent cause for degradation was invaders outcompeting and replacing native species (58 %). Other causes for degradation were a decline in native species richness (23 %), a change in species composition or structure (21 %), the depletion of the native seed bank, changes in soil properties or resource availability (11 %), an increase in litter (11 %) or a change in disturbance regimes (8 %) (Figure 2c).

Sixty-three percent (101) of studies had the overall objective to control invasive species and/or to promote native species. Other objectives included restoration of degraded sites (10 %) and forest restoration (7 %). The rest of the studies investigated the impact of invaders on the native ecosystem (11 %), looked at competition between native and alien plant species (8 %), or at costs and benefits of restoration (economic study) (1 %).

If invasion control was the explicit aim of the study, the main measure adopted was mechanical control (33 %) followed by herbicide application (19 %). Other common approaches of invasion control were burning (11 %), alteration of soil nutrients (11 %) or a combination thereof (13 %). Follow-up methods or biological control measures were only adopted in two studies (Figure 2d).

Sixty-five percent of the studies, which had the overall aim to control invaders and promote natives, implemented measures that went beyond the removal of alien plants. The most prevalent measure adopted was re-introducing native plant species by sowing (64 % of the studies) followed by soil improvement (47 %) and planting of desirable native species (27 %). Other measures adopted were change of grazing regime (9 %), manipulation of hydrological regime in riparian ecosystems (7 %), and removal of competitive neighbor plants (4 %) (Figure 2e). Reasons for additional measures as described by the authors were lack of native species establishment (44 %) and/or depleted native seed bank (4 %), or competitive advantage of the invader (e.g. through elevated nutrients) (20 %). Some studies adopted additional measures to prevent alien species spread or reduce the susceptibility of the site to invasions (11 %). Others described the system as "resistant to restoration" because of positive feedback loops established by the invader for example in connection with a change in the fire regime (11 %). Eleven percent of the studies justified additional measures because the site was highly degraded (e.g. soil contaminated with pesticides and fertilizer).

Twenty-two percent of the studies reported on long-term success of which nine percent were successful, eleven percent were partly successful and two percent were described as not successful.

If invasion control was not the explicit aim of the study, invaders were described as influencing the success of restoration activities through a dominance of the invader either after active restoration (36 %) or before restoration, hindering the establishment of native species (18 %). On the other hand alien species were used for restoration of degraded sites in 18 % of the studies or were used to facilitate the establishment of native species (e.g. in forest restoration) (18 %).

Discussion

An overall comparison of published restoration studies revealed that invasion control is not as common as other types of restoration (e.g. forest restoration). However, a closer look at the sub-group of invasion-restoration studies shows a clear link between invasion and restoration ecology in the scientific literature. The importance of restoration for the management of alien plant invasion is reflected in our finding that 65% of the studies with the aim of controlling the invader and promoting native species adopted measures other than the removal of the invader. At the same time, invasives play an important role in restoration studies that have other objectives (e.g. forest restoration), interfering with restoration actions by hindering the establishment of native species. Interesting is the finding that in some cases alien species are even used in the process of restoration (Lavoie et al. 2005, Jurado et al. 2006).

To find ways of improving the management of alien plant invasions we sought to identify "shortcomings" of invasion-restoration studies that could be overcome by combining efforts of invasion and restoration ecologists. The majority of the restoration studies focusing on alien invasions report causes of degradation other than alien invasions. This finding reflects a very important issue concerning the management of alien plant invasions, that invasions are often considered a symptom rather than a cause of degradation (MacDougall and Turkington 2005). The consideration of not only the invasive species but the whole ecosystem context with its multiple interacting factors during restoration activities provides a number of potentially different management and restoration options (Firn et al. 2008). For example, as shown in our results, changes in soil nutrient properties are viewed as a main cause for degradation through alien invasion. Restoration measures to address this problem include either reduction or addition of soil nutrients in an attempt to reverse the disturbance to the ecosystem. This nutrient change to the ecosystem, however, may in fact only be symptomatic of other changes within the ecosystem (Suding et al. 2004, Fisher et al. 2009a, Fisher et al. 2009b).

Another example is competition by invasive plant species. Competition was by far the most frequently investigated process of ecosystem degradation caused by the invader and the most commonly adopted measure to address this problem was the removal of the invader. However, the removal of alien plant species alone often does not have lasting and effective outcomes, with differing removal methods having the potential to provide different responses and interactions within the managed/restored native plant community (Flory and Clay 2009). Firstly, the removal of invasive species alone might not allow ecosystems to recover as some invaders leave behind legacies which change the condition of the habitat preventing native species from recolonisation (Zavaleta et al. 2001, Fisher et al. 2006, Fisher et al. 2009b) and or promoting secondary invasions (Galatowitsch and Richardson 2005, Beater et al. 2008). Secondly, restoration efforts can have unforeseen consequences that exacerbate rather than mitigate the problem that initiated the restoration effort (Hobbs and Richardson 2011).

These examples show that restoration actions designed specifically to mitigate the known change may neglect other co-existing alterations to the ecosystem state, leading to unexpected results such as replacement by a new alien species, or deaths of re-introduced native species (Vilà and Gimeno 2007, Beater et al. 2008, Blackburn et al. 2009, Bergstrom et al. 2009).

The finding that mechanical control of alien plant invasions is by far the most common control method is also surprising as it is presumably also the most expensive. Nuñez and Pauchard (2010) argue that developed countries are in the position to allocate funds for sophisticated control methods, while developing countries might have fewer funds but abundant low cost labour, which is a major advantage. On the other hand Kull et al. (2011) and Wilson et al. (2011) state that control of alien invasions in developing countries is often in direct conflict with uses of invasives (e.g., for restoration of degraded lands or as a resource for poor communities).

Surprising is that follow-up control and measures of biological control were only adopted in two studies respectively. Invasive species are often characterised by high propagule pressure therefore follow-up controls are essential to prevent re-invasion and should therefore be included into restoration projects (Gaertner et al. 2012).

Our findings show that there is an established link between restoration and invasion ecology, however our results also show that the management of alien plant invasion and restoration after alien invasions respectively could be improved. Although the majority of the studies identified invasive species as symptoms of habitat degradation rather than cause, restoration activities mostly focused on controlling the invader while other underlying causes for degradation were neglected. Here a focus on the causes of degradation rather than symptoms will increase the efficiency of restoration efforts (Vilà et al. 2011).

As reflected in our results, another concern with the current approach of dealing with alien invasions for both fields is the limited combination of theoretical and practical aspects. This deficiency leads to difficulties in translating theoretical concepts into effective management actions. The "knowing-doing gap" between knowledge acquisition and its implementation has been the subject of recent discussion in different fora, mainly conservation practice disciplines (e.g. Knight et al. 2008) and has also been verified for the field of invasion ecology (Esler et al. 2010, McGeoch et al. 2010, Richardson et al. 2010, Shaw et al. 2010).

We believe that the identified shortcomings could be addressed by closer collaboration between restoration and invasion ecologists including practitioners. In the next paragraph we present a nine-step framework focusing on invasion management in nine steps integrating restoration and invasion ecologists and practitioners.

An integrated framework for the management of alien plant invasions

In Figure 3, we present an integrated framework for an improved management of alien plant invasions based on the findings of our literature analysis. Our framework incorporates ecosystem interactions and invasive species into restoration planning and goal setting (Norton 2009, Palmer and Filoso 2009). This inclusion will provide the opportunity to better integrate invasion and restoration ecology (Firn et al. 2010, Traveset and Richardson 2010, Hobbs and Richardson 2011), which will potentially result in more effective restoration projects with successful management of invasive species (Figure 3).

Firstly, it is important to decide whether restoration management interventions beyond the removal of alien plants are necessary. If ecosystem processes and function are altered, restoration actions beyond the removal of the invader will likely be necessary. In this case restoration and invasion ecologists will need to consider the causes of degradation and resultant ecosystem changes when setting goals, aims and measurements of success for the restoration project (Figure 3, Step 1-3). Once restoration strategies and research methods have been developed (Step 4) practitioners should be involved to develop restoration actions (Step 5). Before and after restoration it is crucial to collect scientific data to investigate species interactions, the effects of disturbances and results of restoration actions (Step 4 and 7). Results of ecological scientific surveys before and after restoration will provide understandings of interactions and evidence to adapt and modify restoration activities as ecosystems respond to management changes (Figure 3 step 6 -8). In the next section we introduce a case study focussed on restoration projects in the Canning River, Perth, south-western Australia utilising the framework to enhance the understandings and effectiveness of invasive species management during restoration.

Case study: Utilising the Framework in Restoration Projects in the Canning River, Perth Western Australia

The Swan River estuary flows through the city of Perth, in the south west biodiversity hot spot of Western Australia (Myers et al. 2000). The Swan River and a major tributary the Canning River were identified by the Australian Government's Coastal Catchment Initiative as areas of very high nutrient levels, requiring action to reduce nutrient levels entering the Swan Canning river system. A suite of 11 restoration projects focused on the conversion of existing heavily invaded urban drainage lines into "Living streams" resulted (SERCUL 2010), utilizing a number of restoration methods such as: retrofitting existing local drainage systems, restoring natural drainage features removing extensive invasions of multiple invasive alien species, and utilising indigenous vegetation to restore natural habitats and improve visual amenity for the residents (Department of Water 2009). A local, community run coordinating body with extensive restoration experience, SERCUL (South East Regional Centre for Urban Landcare), is responsible for the coordination and the collaborative stimulus for the 10 Project Partners delivering the management, implementation and monitoring phases for these 11 restoration projects. A workshop (facilitated by Author 2, JF) was conducted with SERCUL staff to identify existing knowledge gaps, which if incorporated into restoration projects, had the potential to enhance the effectiveness of restoration in these highly disturbed and invaded ecosystems (Fisher 2011). Critical knowledge gaps identified were: 1. the need to gain a greater understanding of the interactions between native and introduced spe-

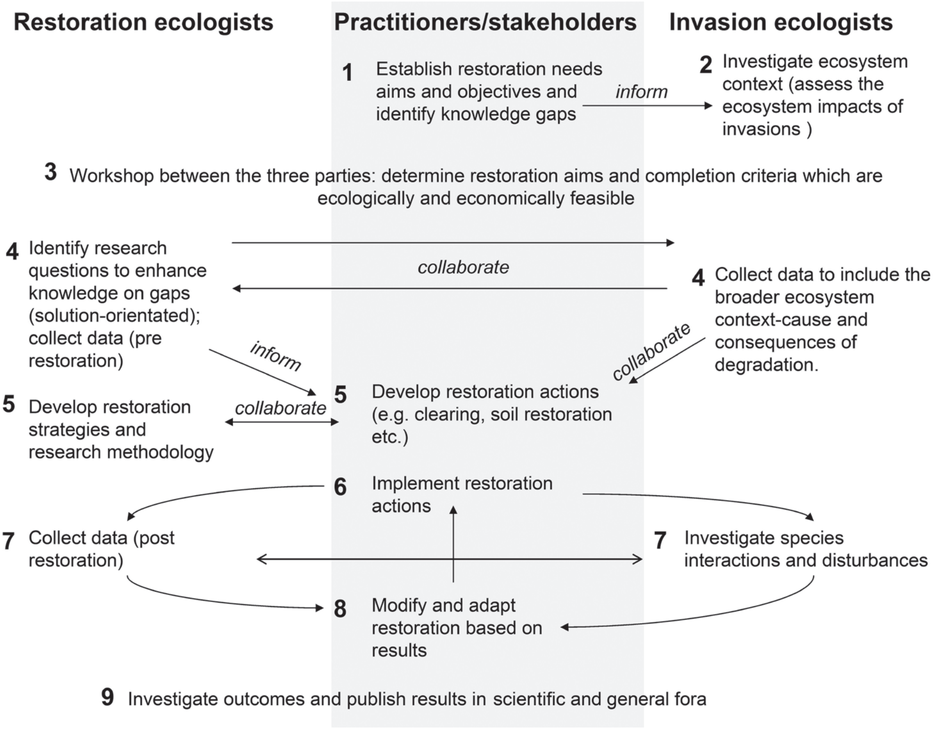

Figure 3. Framework for restoration of sites following alien invasion incorporating practitioners/stakeholders, restoration ecologists and invasion ecologists. Step 1: Practitioners approach restoration ecologist and invasion ecologists with a specific need and aims for ecosystem restoration and an understanding of knowledge gaps. Step 2: Before restoration aims and objectives can be finalised invasion and restoration ecologists assess the impacts of disturbance and invasion on the ecosystem. Step 3: Workshop with restoration and invasion ecologists and practitioners/stakeholders to determine restoration aims and completion criteria which are both ecologically and economically feasible. Depending on the degree of degradation, restoration goals will range from re-establishing a natural ecosystem state, focusing on biodiversity components and ecosystem function, to "only" restoring ecosystem processes and functions. Step 4: Once restoration aims have been identified restoration ecologists identify research questions to enhance knowledge gaps (e.g. how can native species be re-established, how can elevated soil nutrient levels be reduced) with invasion ecologists investigating the broader ecosystem context (e.g. is the invader the cause for ecosystem degradation or are there other underlying causes (e.g. anthropogenic disturbances). Step 5: In a collaborative effort restoration ecologists and practitioners develop restoration actions and research methodology. Before, during and after implementation of the restoration actions, restoration and invasion ecologists collect data to monitor restoration success and investigate species interactions and disturbances. Steps 6–8: Communicate findings to practitioners and modify and adapt restoration accordingly. The iterative feedback of research results into practice guarantees ongoing monitoring and improvement of practice. Step 9: Last, but not least, restoration and invasion ecologists investigate restoration outcomes and publish the results to make the findings available to the scientific and wider community.

cies, terrestrial and aquatic, both before and after restoration actions and 2. the lack of a measured range of ecological indicators which would identify ecosystem restoration trajectories and success. To this end SERCUL, restoration ecologists and practitioners, developed and implemented the framework recommended in this paper (Figure 3), and utilised restoration and invasion ecologists' (Author 2, JF) expertise in the early project development phases and ongoing analysis and interpretation phases of the 11 restoration projects (Figure 3, Steps 1,2,3, 7 and 8). The identified knowledge gaps have been utilized to develop research, monitoring and evaluation programs, including an integrated ecosystem assessment to provide greater understandings of the outcomes of the restoration projects (Fisher 2011). Following the identification of these key knowledge gaps, (Figure 3, Step 1) objectives were defined and baseline data collection criteria developed and implemented, based on the restoration and invasion ecologists' input (Figure 3, Steps 1, 2, 3 and 4). The outcome has been the development of a rigorous and scientifically valid monitoring and evaluation program (publications in preparation) (Figure 3, Steps 5, 6, 7), with opportunities and scope to adapt restoration actions (Figure 3, Step 8). The collaborative approach has resulted in an extensive accumulation of knowledge from numerous, often untapped sources, which have then been incorporated into the design and implementation of all projects. The benefits of collaborative outcomes have been cost and time reductions, a bridging of the knowing-doing gap (Esler et al. 2010), restoration methods determined in an informed and agreed manner incorporating both the doer and the long term manager, expansion of knowledge across all stakeholders with an inherent acquisition of knowledge incorporated into normal practice.

During the implementation of the framework SERCUL identified, as a high priority, the need to develop an enhanced knowledge base with a greater understanding of the ecosystem mechanisms which influence restoration pathways. The gathering of such data provides the added advantage of being able to assign a high level of causal inference between the restoration actions and the ecosystems' response to these actions (Figure 3, Steps 6, 7, 8) (Cottingham et al. 2005). The collaborations forged during the implementation of the framework have led to the incorporation of expanded monitoring and research strategies and methodologies, including measurements of the diversity of ecosystem components and interactions to better understand the implications of restoration actions on ecosystem processes and function. The restoration practitioners are now able to provide, in line with their long term aims, effective evaluation of projects, and credible guidance for future restoration projects and ecological understandings of the newly developed "Living Streams", while obtaining a greater understanding of the processes and functioning of the pre and post restored ecosystems (Figure 3, Step 9) (Clark et al. 2011). The extensive collaboration which has occurred as part of this project and the practitioners' needs to understand more about the ecosystem effects of their restoration actions has changed numerous stakeholders methods and understandings and the on going manner in which assessment and measurement of the effectiveness of nutrient intervention and invasive species management programmes are conducted.

Conclusion

While a link between the disciplines of invasion and restoration ecology exists in the scientific literature, there is still room for improvement with the aim of strengthening the practical outcomes of both fields. Specifically, invasive species, the ecosystem context and the feedbacks between the two are important considerations to include into restoration planning and goal setting. Understanding the consequences of restoration actions provides a mechanism to more rapidly respond to and adapt management actions to build resilient ecosystems. A combined effort from both disciplines with a focus on understanding the interactions of species, both native and non-native, could greatly improve our understanding of ecosystem shifts thus potentially providing new and different solutions to more effectively protect biodiversity and manage alien species during restoration actions.

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Appendix S1

Key journals used for a literature review on linkage between the disciplines invasion biology and restoration ecology. Selection of key journals followed Pyšek et al. (2006)

APP1

Key journals invasion biology	Publisher	Scope of Journal (relevant to our study)
Applied Vegetation Science	Wiley Blackwell, International Association for Vegetation Science	Any community-level topic relevant to human impact on vegetation, including amongst others restoration of plant communities.
Austral Ecology	Wiley-Blackwell, The Ecological Society of Australia	Experimental, observational or theoretical studies on terrestrial, systems.
Biodiversity and Conservation	Springer	Articles on all aspects of biological diversity - its description, analysis and conservation, and its controlled rational use by humankind.
Biological Invasions	Springer	Patterns and processes of biological invasions in terrestrial ecosystems. Management and policy issues related to conservation programs and the global amelioration or control of invasions.
Diversity and Distributions	Wiley-Blackwell	Application of biogeographical principles, theories, and analyses to problems concerning the conservation of biodiversity including the study of biological invasions.
Ecology	Ecological Society of America (ESA)	All aspects of ecology.
Ecological Applications	Ecological Society of America (ESA)	Integration of ecological science and concepts with their application and implications. Papers that develop the basic scientific principles on which environmental decision-making should rest, and those that discuss the application of ecological concepts to environmental problem solving, policy, and management.

Key journals invasion biology	Publisher	Scope of Journal (relevant to our study)
Ecological Monographs	Ecological Society of America (ESA)	Empirical and theoretical advances in the field of ecology.
Ecosystems	Springer	Ecosystems services and management.
Journal of Ecology	British Ecological Society	All aspects of the ecology of plants in terrestrial ecosystems.
Journal of Vegetation Science	Wiley Blackwell, International Association for Vegetation Science	Methodological and theoretical studies, and descriptive and experimental studies of plant communities and plant populations.
Oecologia	Springer	Conservation Ecology
OIKOS	Wiley Blackwell, Nordic Society OIKOS	Aspects of ecology, defined as organism-environment interactions.
Plant Ecology	Springer	Findings of pure and applied research into the ecology of vascular plants in terrestrial and wetland ecosystems.
Wetlands	Springer	All aspects of wetlands biology, ecology, hydrology, water chemistry, soil and sediment characteristics, management, and laws and regulations.

Appendix S2

Types of restoration as defined by the main aim of the study

APP2

Types of restoration	Examples
Restoration after anthropogenic disturbances	Restoration of old fields, restoration after mining
Wetland restoration	Restoration of riparian ecosystems and wetlands, restoration of water bodies
Erosion control	Restoration of road sides
Forest restoration	Restoration of degraded forest or re-establishment of secondary forests
Grassland restoration	Restoration of grasslands after agricultural use
Restoration after alien invasion	Studies with an explicit focus on the control of invasive alien species
Restoration of arid lands	Restoration of degraded rangelands, dune restoration and savanna restoration
Shrubland restoration	Restoration of shrublands after degradation
Soil restoration	Restoration of soils after contamination or agricultural use
Species restoration	Re-introduction of specific (endangered) species

Appendix S3

Variables and categories used for analysing the linkage between Restoration Ecology and Invasion Biology (methodology follows Aronson et al. 2010).

APP3

Category	Key words and Definitions
Study objective	Is invasion control the explicit aim?
Country	Country where restoration/alien invasion took place
Ecosystem in which the study was conducted	Grassland, forest, wood and savanna, shrubland, arid and semi-desert and desert, rivers, other wetlands, marine and costal, urban, human modified and transformed, other or unclassified
Causes of degradation (according to UNEP 2003, modified)	Deforestation Overgrazing Agricultural activities (other than grazing) Overexploitation of vegetation (e.g. fuel wood consumption) Industrial activities (Alien) invasion (includes native invasions)
Causes of degradation (invader)	Replacing/outcompeting native plants Decline of native species richness Changes in native species composition/structure Changes in soil properties (e.g. nutrient enrichment) Changes in native soil seed bank (depletion) Change of disturbance regimes (e.g. fire regime) Others (e.g. impact on native fauna)
Invasion control	Biological control Mechanical control Herbicide control Alteration of soil nutrients Follow-up control Burning
Restoration approach; measures implemented beyond removal of invader	Sowing or planting Soil improvement (i.e. mulching, ploughing, top soil removal) Change of grazing regime Manipulation of hydrological regime Removal of competitive neighbour plants Solarisation
Reasons for additional measures	Lack of native species establishment / depleted native seed bank Competitive advantage of invader Prevent alien species spread/reduce susceptibility to invasion System resistant to restoration/break positive feedback loop (e.g. changes in fire regime) Highly degraded site (e.g. after agricultural use) Nutrient enriched soils Not specified