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REVIEW

Lessons learned from invasive plant control experiments: a systematic review and meta-analysis

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Summary

1. Invasive plants can reduce biodiversity, alter ecosystem functions and have considerable economic impacts. Invasive plant control is therefore the focus of restoration research in invader-dominated ecosystems. Increasing the success of restoration practice requires analysis and synthesis of research findings and assessment of how experiments can be improved.

2. In a systematic review and meta-analysis of invasive plant control research papers, we asked: (i) what control efforts have been most successful; and (ii) what invasive plant control research best translates into successful restoration application?

3. The literature evaluated typically described experiments that were limited in scope. Most plot sizes were small (< 1 m^2), time frames were brief (51% evaluated control for one growing season or less) and few species and ecosystems (predominantly grasslands) were studied throughout much of the literature. The scale at which most experiments were conducted potentially limits relevance to the large scales at which restorations typically occur.

4. Most studies focused on invasive species removal and lacked an evaluation of native revegetation following removal. Few studies (33%) included active revegetation even though native species propagule limitation was common. Restoration success was frequently complicated by re-invasion or establishment of a novel invader.

5. Few studies (29%) evaluated the costs of invasive species control. Additionally, control sometimes had undesirable effects, including negative impacts to native species.

6. *Synthesis and applications*. Despite a sizeable literature on invasive plant control experiments, many large-scale invasive plant management efforts have had only moderate restoration success. We identified several limitations to successful invasive species control including: minimal focus on revegetation with natives after invasive removal, limited spatial and temporal scope of invasive plant control research, and incomplete evaluation of costs and benefits associated with invasive species management actions. We suggest that information needed to inform invasive plant management can be better provided if researchers specifically address these limitations. Many limitations can be addressed by involving managers in research, particularly through adaptive management.

Key-words: alien species, control, herbicide, novel invader, propagule limitation, restoration, revegetation, weed

Introduction

Invasive plant control is a significant challenge for natural resource management. However, as Hulme (2006) aptly stated, 'much research to date is primarily concerned with quantifying the scale of the problem rather than delivering robust solutions.' Ecosystem restorations are particularly prone to invasion, as the restoration process results in disturbance and increased resource availability (D'Antonio & Meyerson 2002; DeMeester & Richter 2009). Despite efforts to understand the characteristics of invasive plants (e.g. Rejmánek & Richardson 1996; Bossdorf *et al.* 2005; Ellstrand & Schierenbeck 2006) and what makes some areas

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more invasible than others (e.g. Stohlgren *et al.* 1999; Alpert, Bone & Holzapfel 2000), invasive plant control efforts in the context of restoration have had mixed success. This is particularly problematic for managers who must translate research into practice (Clewell & Rieger 1997; Reinhardt 2004; Young, Petersen & Clary 2005). Managers need research to be part of the solution to improve invasive plant control and scientists have been criticized for not closing this gap (Stromberg *et al.* 2009).

A critical function of invasive plant control research is to provide information to guide practitioner decision-making. Ecosystem- and invader-specific information generated by scientific investigation is practical but surprisingly lacking (Flory 2010). General conclusions may be of greater utility, but are also uncommon. Making informed decisions about effective invasive species control requires information on two fronts: methods and approaches (Epanchin-Niell & Hastings 2010). Information regarding *methods* concerns successful tools for controlling invasion and promoting desirable species. Once methods are established, questions about *approaches* can be addressed, e.g. the best spatial approach for control, level and length of effort required for invader control, and appropriate monitoring. The link between science and management may be weakest regarding questions about broad approaches (Stocker 2004).

From previously published and more narrowly focused reviews of invasive plant control, the challenges associated with translating science into practice emerge (Stewart *et al.* 2008). Despite advances in control methods and native species establishment techniques, rates of successful transition from an invaded system to a native community can be low. Research links restoration failure following invasive plant control to prolonged invader persistence and reinvasion, extremely dry conditions and native propagule limitation (Aronson & Galatowitsch 2008; Prach & Hobbs 2008; James & Svejcar 2010). Similar problems emerge in practice; a survey of Australian weed management programmes found control to result in reinvasion or a novel invasion, rather than recovery of native plant species (Reid *et al.* 2009). Another challenge for optimal control on a landscape-scale is conducting management with limited financial resources. Explicit consideration of control strategy cost (e.g. methods cost, length of control required, follow up costs) is appropriate. Uncertainties in invader response to control efforts limit predictability of management expenditures and challenge this approach, resulting in over-allocated management efforts or insufficient invader control (Epanchin-Niell & Hastings 2010). Given that generalities are difficult to determine without considering outcomes from many individual studies, a broad survey of the literature is required to bridge the gap between experiments and application for invasive plant management.

A quantitative assessment of similar studies can identify evidence-based recommendations for improving the application of invasive plant control research to management. In an effort to gain insight into translating invasive plant control research for application to restoration, we asked two broad questions:

1. What control efforts, tools, or approaches for invasive plant control have been most effective across invaded ecosystems?
2. How are invasive plant control methods best evaluated for relevancy to restoration practice and translated into successful restoration application?

We used published, quantitative assessments of invasive plant control in a restoration context to address these questions and systematically reviewed invasive plant control research across multiple species and ecosystems. In a meta-analysis, we examined both invasive and native plant response to common control methods. We suggest a framework for improving invasive plant control and restoration research and for translating experimental findings for practitioners managing invaded lands.

Materials and methods

LITERATURE SEARCH

We used ISI Web of Knowledge, Scopus, Ecology Abstracts, Science Direct, JSTOR, Digital Dissertations and relevant grey literature sources (The Nature Conservancy http://www.conserveonline.org; New Zealand Department of Conservation http://www.doc.govt.nz/publications/science-and-technical/online-catalogue/) to generate a database of publications through 2009 that quantitatively assess invasive plant species control efforts in an ecosystem restoration context. We used the following search terms: (invasive species or exotic species or alien species or weed or nonnative species or non-native species or introduced species) AND (restor* or control or remov* or eradicat*) AND (plant* or seed* or herb* or flora* or veget* or botan* or tree or shrub). The search produced more than 10 000 unique references which were screened systematically for inclusion in the review (sensu Pullin & Stewart 2006). Three criteria determined study inclusion: (i) published quantitative invasive or native plant response to control efforts, (ii) studied invasive plant(s) in a field context (not a laboratory, greenhouse or agricultural setting), and (iii) any revegetation focused on native species. Based on our *a priori* criteria, most papers were excluded by their title because they were from an irrelevant discipline. Relevant title publications were assessed at full text. We excluded duplicate records, i.e. multiple papers that summarized the same experiment. Additionally, papers that implemented biological control were excluded, as the use of classical biocontrol to control invasive plants was recently reviewed by Thomas & Reid (2007). This manuscript, therefore, focuses on other control options.

SYSTEMATIC REVIEW

The systematic review synthesized references by collecting data on the following questions: (i) Where do invasive plant control experiments occur? (ii) What are the characteristics and origins of the invasive plants? (iii) What is the experimental/study approach? (iv) What are the experimental treatment and sampling plot sizes? (v) What is the length of time for control efforts? (vi) What is the length of time for post-control monitoring? (vii) Are repeated long-term control efforts necessary for invasive plant management? (viii) Are target native plants actively revegetated? (ix) If control efforts are unsuccessful, what are the reasons for the lack of success? (x) Do researchers consider the cost of control efforts in their analysis?

We performed frequency and distribution counts with each publication as an experimental unit to examine responses to the above questions. We also used Pearsons Chi-Square analysis to determine if using a particular control method (i) affected the need for long-term control, (ii) negatively affected non-target, native species and (iii) affected the likelihood of invasion by novel species post-control. We analysed the five most frequently used control methods (herbicide, cutting, burning, hand pulling/removal, native revegetation), as these techniques were used in at least 10% of studies. Our Bonferroni corrected *P*-value for the five tests was 0·01.

META-ANALYSIS

To evaluate invasive and native plant response to common control methods, we performed a meta-analysis using standard meta-analytical techniques (Osenberg *et al.* 1999; Pullin & Stewart 2006; Tyler, Pullin & Stewart 2006). Our meta-analysis was based on a subset of studies from the systematic review that (i) reported quantitative estimates for biomass, cover or density of the invader and/or native species (these response variables allowed for the highest number of comparisons between studies), (ii) published values quantitatively or in tabular form and (iii) had a study design with either a pre-treatment/post-treatment or control/treatment comparison.

Many studies in our data set documented a single, unreplicated restoration and therefore did not report measures of variation. To include these studies in our analysis, we chose an effect size metric that does not rely on variation estimates, the response ratio = $\ln(X_E/X_C)$, where X_E = mean of the experimental group and X_C = mean of the control group (Osenberg, Sarnelle & Cooper 1997; Osenberg *et al.* 1999); positive response ratios reflect an increase in a response variable. Although this metric may misrepresent the true mean response by over-emphasizing high-variability studies, we chose this approach to maximize the number of studies included in the analyses, as the loss of information through study selection may be a serious problem with estimating true effect size (Gurevitch *et al.* 1992).

When studies reported multiple responses through time, we calculated a response ratio for the longest control period to avoid problems with non-independence of data. For multifactorial studies, we compared only single factor treatments, facilitating comparison with the largest number of studies (Table S1 Supporting Information). We calculated mean response ratios for broad control categories: burning, cut and/or removal, herbicide and native revegetation. Because native revegetation (seeding or planting) typically follows invasive control for site preparation, response ratios for native revegetation reflect outcomes of both invasive control and revegetation.

Results

Our search returned 355 papers published between 1960 and 2009 (Appendix S1 Supporting Information) that evaluated invasive plant control in a restoration context. Most of these studies (78%) assessed the effects of control methods in an experimental setting; the remainder assessed effects with before-and-after comparisons from real restorations or adaptive management projects.

STUDY SPECIES AND STUDY LOCATIONS

The most commonly studied species were *Centaurea maculosa* Lam. and *Phalaris arundinacea* L. (Table 1), but most species were addressed by a single study (Table S2 Supporting Information). Of the 110 species that were included in the study, most were perennials (87%, 96 species), 39 of which were forbs, 38 were woody species, and 19 were grasses. Other perennial species that were the focus of 10 or more papers were *Euphorbia*

Table 1. Invasive plants that were the focus of control efforts for more than three studies (number of studies in each location in parentheses)

Species	No. of studies	Location of study	Life cycle	Structure
Centaurea maculosa (spotted knapweed)	21	MT (17), MI (2), WA, WY	P/B	F
Phalaris arundinacea (reed canary grass)	15	WA (3), IN, MN (5), TN, WI (3), OR, MT	P	G
Euphorbia esula (leafy spurge)	15	MT (6), ND (5), NE (2), SD (2)	P	F
Pteridium aquilinum (western brackenfern)	13	UK (11), Bulgaria (2)	P	F
Phragmites australis (common reed)	11	VA (2), DE, Ontario Canada, South Africa, NJ, MA, CT, Israel, France, Portugal	P	G
Myriophyllum spicatum (Eurasian watermilfoil)	10	WA, NY, WI (3), MN (3), MI (2)	P	F
Bromus tectorum (cheatgrass)	9	MT (2), WA (2), CA, CO (2), OR, UT	A	G
Tamarix ramosissima (saltcedar)	9	NM (4), CA, NV, UT, AZ, CO	P	W
Bromus inermis (smooth brome)	7	AZ, WA, Saskatchewan CN, NE(2), SD, MN	P	G
Agropyron cristatum (crested wheatgrass)	7	Saskatchewan CN (7)	P	G
Potentilla recta (sulfur cinquefoil)	7	MT (6), OR	P	F
Cirsium arvense (Canada thistle)	6	MT, UK, Germany, ND (2), WY	P	F
Alliaria petiolata (garlic mustard)	5	OH (2), IL, MO, MA	B/A	F
Microstegium vimineum (Japanese stiltgrass)	5	IN (2), NC (3)	A	G
Centaurea solstitialis (yellow star-thistle)	5	CA (4), OR	A	F
Taeniatherum caput-medusae (medusahead)	4	CA (3), OR	A	G
Imperata cylindrica (cogongrass)	4	MS (2), New South Wales Australia, FL	P	G
Spartina alterniflora (smooth cordgrass)	4	China (3), WA	P	G
Eichornia crassipes (water hyacinth)	4	CA (2), Kenya, Mexico	P	F
Butierrezia sarothrae (broom snakeweed)	4	NM (3), WY	P	W
Lepidium latifolium (perennial pepperweed)	4	NV, CA (3)	P	F

A, annual; P, perennial; B, biennial; F, forb; G, graminoid; W, woody (shrub/tree).

esula L., *Pteridium aquilinum* (L.) Kuhn, *Phragmites australis* (Cav.) Trin. ex Steud. and *Myriophyllum spicatum* L. A few studies (9%) addressed groups of invaders, e.g. arable weed species, exotic grasses.

More studies (39%) were conducted in temperate grasslands than any other ecosystem (Fig. 1). Most studies (74%) were located in North America, with Australia and New Zealand (9%), Europe (8%), Africa (6%), Asia (2%) and South America (1%) providing locations for all other studies.

INVASIVE PLANT CONTROL METHODS

More than 55% of the studies applied herbicide for invasive plant control, 34% employed cutting techniques (including mowing, weed whipping, string trimming or using a chain saw) and 24% evaluated burning (Fig. 2). Most studies evaluated either one or two control methods (46% and 31% of studies, respectively); 19% evaluated three or more control methods (no studies evaluated more than 6 techniques). The most common herbicide used was glyphosate (42% of studies), followed by 2,4-D (17%), picloram (14%), and triclopyr (12%). Five per cent of studies did not specify the herbicide used. Only 33% of studies attempted active revegetation (Fig. 2). Propagule limitation was stated or implied to be important in 37% of studies but only 23% of these planted or seeded native species during the experiment. In some cases, active revegetation was intended to serve as a control method, in other cases it was used solely for reestablishing the native plant community after invasive plant control.

Forty-six per cent of studies applied invasive plant control methods to plots that were ≤30 m^2, including 11% that had treatment plots ≤1 m^2 in size (Fig. 3a). The area sampled for

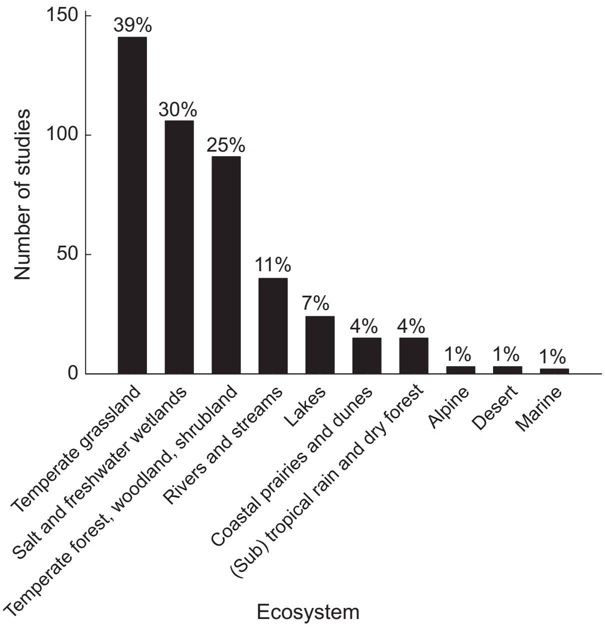

Fig. 1. Ecosystems where each study in the systematic review was conducted. Seventy studies were classified into two ecosystems and 15 studies were classified into three ecosystems.

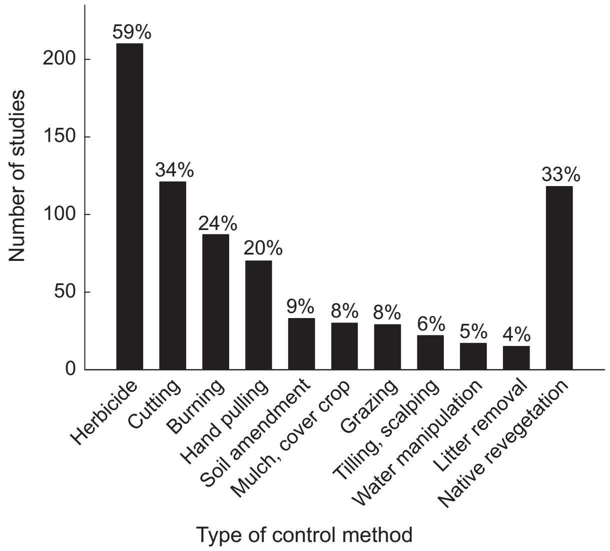

Fig. 2. The type of control methods used in studies in the systematic review. Studies evaluating different aspects of one type of control (e.g. different timing of an herbicide application) were counted once for that type of control method.

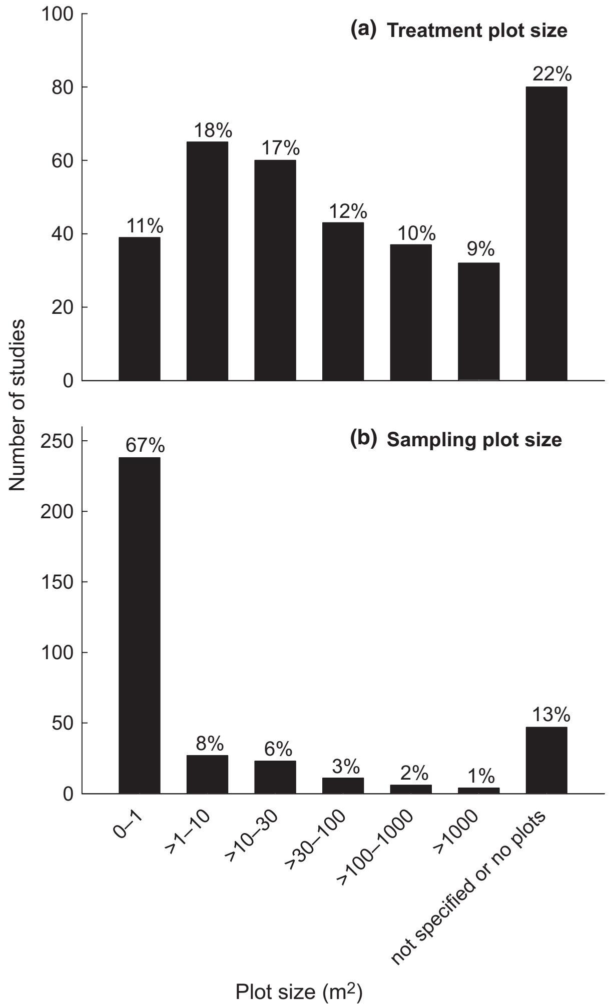

Fig. 3. Treatment and sampling plot size for each study in the systematic review.

treatment effects was usually ≤1 m^2 (Fig. 3b). Several studies (22%) did not specify the size of the area to which treatment was applied or plots were not used; 13% of studies did not report sampling plot size or had no plots.

For 61% of studies, the longest period of invasive plant control application was ≤1 year, with 28% evaluating a one-time control application (Fig. 4a). Only 7% of studies involved a control period of > 5 years. Upon completion of control efforts, 52% of studies monitored response (of invader and/or desirable species) for ≤1 year (Fig. 4b).

INVASIVE AND NATIVE PLANT RESPONSE TO CONTROL METHODS

Response ratios for the meta-analysis were calculated from our data set for 84 papers; 49 reported invader response only, 10 reported native response only and 25 reported both. Although invasive plants were reduced by control efforts, gains in native species were limited; native response ratio confidence intervals usually bracketed zero (Fig. 5). Herbicide most

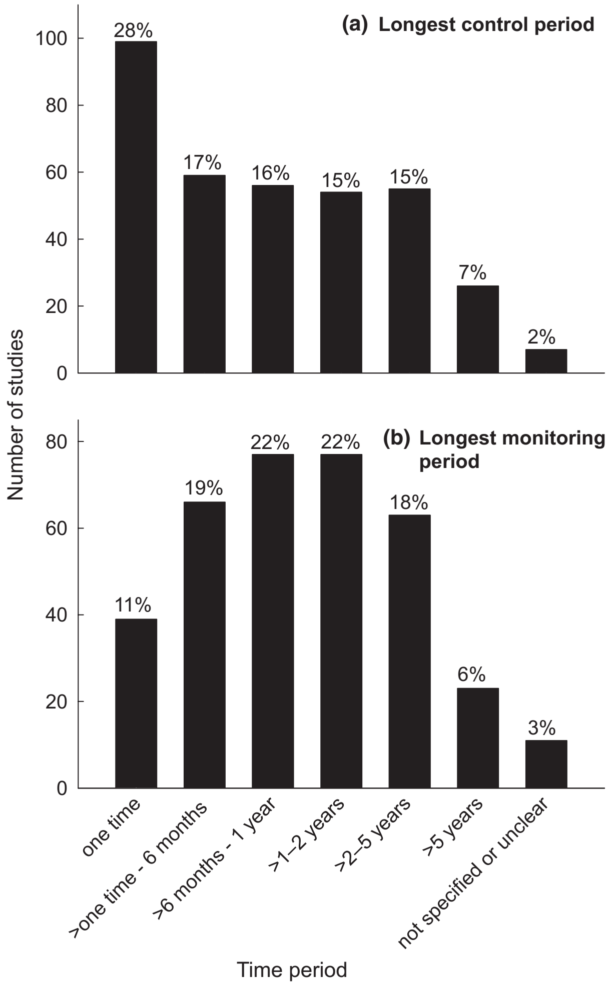

Fig. 4. (a) The longest period of time that invasive plant control was applied and (b) the length of time for which response of the invasive plant and/or the desirable vegetation was monitored upon completion of control efforts.

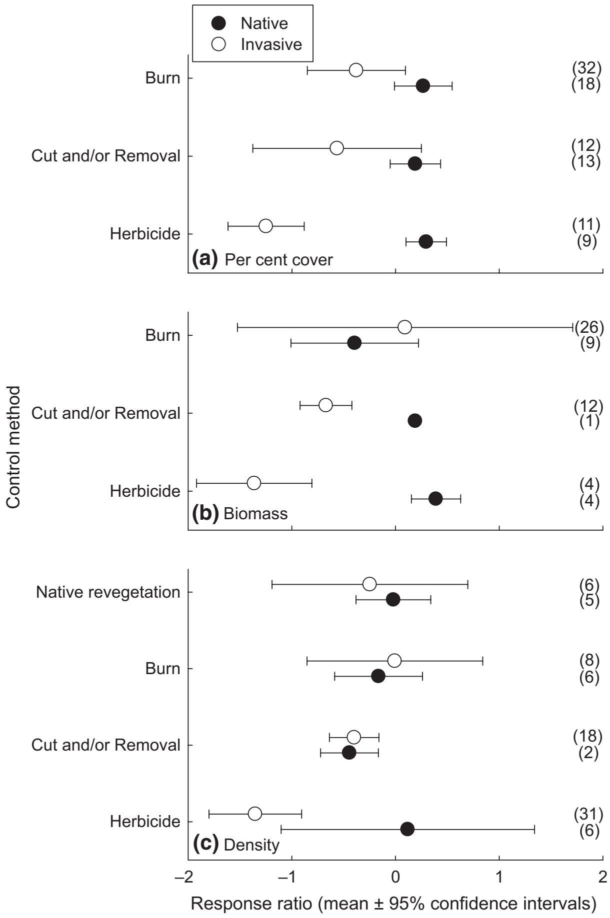

Fig. 5. Meta-analysis results on effects of control methods on per cent cover, density and biomass of native and invasive plants (number of studies summarized per response ratio is given to the right of each graph). Response ratio means and confidence intervals allow for relative comparison between treatment responses. Studies reporting 'fell and remove', 'cleared', 'mechanical removal', 'grazed', 'clipped' and 'mowed' were combined into the 'cut and/or removal' category.

effectively reduced invasive plant cover, density and biomass but this was not accompanied by a substantial increase in native species. Overall, burning reduced native biomass and increased invasive biomass. Studies employing native revegetation resulted in little gain in native density and only a slight reduction in invader density (density was the only response variable for which enough studies could be compared for the meta-analysis). Large confidence intervals for some response ratios indicate highly variable outcomes for these control methods.

CHALLENGES TO AND COSTS OF EFFECTIVE INVASIVE PLANT CONTROL

Most studies (71%) did not consider the economic cost of control, despite potentially significant budgetary implications from the research; almost 60% of studies reported that repeated, long-term efforts will be needed to control invasive plants. Long-term control was significantly more likely to be needed in studies where herbicide (Pearson X^2 = 9·4,

P = 0·002) or hand-pulling/removal (Pearson X^2 = 8·3, P = 0·004) was employed. No other control methods had a significant effect on the need for long-term control. More than 30% of studies documented that invasive plant control efforts directly or indirectly negatively affected non-target, native species; these were primarily herbicide use studies (Pearson X^2 = 7·3, P = 0·007). In some cases, the negative effect was a direct result of long-term control efforts.

More than 25% of the studies found that control methods resulted in an open niche, allowing novel invaders to establish. Novel invaders were more likely to occur when hand-pulling/invader removal were used (Pearson X^2 = 11·5, P = 0·0007); no other control method had a significant impact on post-control invasion by novel species.

Discussion

Our review and meta-analysis of invasive plant control research revealed important generalizations for restoring invasive plant-dominated ecosystems and common limitations to applying experimental results to practice; these illuminate several ways in which invasive plant control research can better inform management.

CONTROL EFFORTS CAN HAVE NEGATIVE ECOSYSTEM IMPACTS

Removal programmes are justified on the basis of invasive plant impacts on ecosystems but control methods may have deleterious effects (Myers *et al*. 2000; Rinella *et al*. 2009). The highly variable outcome of any control effort (e.g. the range of outcomes for the effect of burning on invader biomass demonstrated by our meta-analysis) emphasizes the importance of reporting results in quantitative studies. Invasive plant control methods can enhance invasibility through resource release and decreased competition (Thompson *et al*. 2001; Minchinton & Bertness 2003), resulting in reinvasion by the invasive plant targeted for control, or colonization by a novel invasive plant. Extensive long-term control programmes are most likely to negatively impact native species. Unfortunately, long-term approaches that utilize multiple treatments and follow-ups (rather than single application strategies) are also more successful at reducing the target invader. As most studies we reviewed suggested that long-term, repeated control methods would be needed to effectively manage invasives, there is a need to consider the costs and benefits of specific methodologies when implementing control programmes. Impacts to native species can be greatest when programmes involve herbicide application (Matarczyk *et al*. 2002; Wootton *et al*. 2005; MacDonald, Scull & Abella 2007). Herbicide was the most commonly implemented and, according to our meta-analysis, the most effective control method for reducing invasives. However, native species response to herbicide was highly variable, probably because this broad-scale approach can hinder native species establishment through seed limitation (Pickart *et al*. 1998; Cosgriff, Anderson & Monson 2004; Foster & Wetzel 2005; Buisson *et al*. 2006). Regardless of control treatment, our meta-analysis revealed that few studies produced gains in native plant cover, density or biomass. A recent opinion paper encourages considering 'no action' as one alternative to intensive control measures, particularly in severely degraded ecosystems (Ewel & Putz 2004). Increasing invader propagule pressure and potential spread to novel sites are both consequences of this option, and should be carefully weighed against negative impacts to native species.

LIMITATIONS IN GEOGRAPHICAL AND TAXONOMIC SCOPE

Our review detected geographical bias: studies were focused largely in North America, while Africa, Asia and South America received little investigation. This is a common slant in invasive plant literature (Pysek *et al*. 2008), although we note the bias of our review towards English-speaking journals. Economic wealth may drive the abundance of research in the US and UK (Leimu & Koricheva 2005). Effective control is difficult to implement even when research is available, but for understudied areas it is an even greater challenge.

Temperate grasslands were the most studied ecosystem type, probably because grasslands may be the most invaded natural habitat (Lambdon *et al*. 2008). Wetlands were second-most studied, and are often noted as more invasible due to increased levels of resources (high fertility and high moisture) (Fox & Fox 1986; Chong *et al*. 2006). Understudied ecosystem types with less common invasions still require research for effective invasive plant control, yet only widespread invasions seem to be heavily studied.

EVALUATION OF CONTROL COMPLICATED BY SHORT STUDY LENGTH

The short-term nature of implementation and monitoring of invasive plant control is often due to logistical and financial constraints. We found that many studies had a limited control implementation time and/or monitoring response period. Assessment of control is compromised by short-term monitoring because long-term conclusions can differ from initial findings (Blossey 1999). For example, in their 5-year study of *P. aquilinum* control, Petrov & Marrs (2000) found that despite good initial control using one application of glyphosate herbicide, *P. aquilinum* recovered and ultimately required additional treatment for control.

Implementing control methods for short time periods can also complicate control method evaluation, as evaluating multi-year control efforts can reveal important outcomes. Long-term studies, such as those focusing on *P. aquilinum* (Pakeman *et al*. 2002; Cox *et al*. 2007), show that the most effective control strategy shifts as the invader is increasingly replaced by native species and different, more precise control methods are needed. Reid *et al*. (2009) showed that long-term programmes result in a higher abundance of native plants than short-term programmes. Few studies reviewed here evaluated control beyond 2 years, so they may overestimate the effectiveness of the initial treatment. Annual differences in climate also justify extension of the length of control programme (Lesica & Martin 2003). To address these complications, some recommend testing a control method over 4 years or more (Paveglio & Kilbride 2000; Wilson *et al.* 2004); only 26% of studies met that criterion.

REVEGETATION IS ALMOST ALWAYS REQUIRED BUT OFTEN IS NOT EVALUATED IN EXPERIMENTS

Only one-third of studies in this review considered propagule limitation in native plant establishment post-control by revegetating natives. This was surprising given that propagules are limiting in many ecosystem restorations (e.g. Kindscher & Tieszen 1998; Sluis 2002; Seabloom *et al.* 2003; Martin, Moloney & Wilsey 2005; Kettenring & Galatowitsch 2011), including those that involve invasive plant removal (e.g. Provencher *et al.* 2000; Masters & Sheley 2001; Hartman & McCarthy 2004). Our meta-analysis revealed that many studies failed to increase native plants even when the invasive species was reduced, which may be partly due to propagule limitation. Thus, active native revegetation may be necessary and deserves more investigation in invasive plant control experiments. By strategically evaluating revegetation as part of invasive plant control experiments, we can determine whether the control methods themselves have negative impacts on native species and whether alternative control strategies need to be developed. Because native species may naturally be seed limited (e.g. Seabloom *et al.* 2003; Cole, Lunt & Koen 2004; Hartman & McCarthy 2004; Harms & Hiebert 2006), propagule reintroduction may be warranted, regardless of control methods used.

ACTIVE REVEGETATION CAN PREVENT FURTHER INVASION

Many studies identified control methods that were successful in limiting target invasive plants. However, successful invasive plant control often leaves open niches for reinvasion or for novel invaders to colonize. Reintroducing propagules of target native species can catalyse the development of the native plant community to serve as a natural barrier to colonization and expansion of undesirable species. Several studies we evaluated demonstrate a biological mechanism by which revegetation can have weed control benefits (Petrov & Marrs 2000; Wilson & Pärtel 2003; Bakker & Wilson 2004; Prober *et al.* 2005). To more completely understand when revegetation is beneficial for controlling future invasions, native revegetation should be better integrated into invasive plant control experiments.

Effective revegetation efforts offer the greatest control. Planting diverse species assemblages can capture resources and space quickly to limit the potential for undesirable species to colonize and persist (Masters & Sheley 2001; Blumenthal, Jordan & Svenson 2003; Fargione & Tilman 2005; Iannone & Galatowitsch 2008). We found that native revegetation treatments slightly reduced invasive species, but native species gains were not appreciable, suggesting this is a critical area for research in order to promote native species establishment. To capitalize on the use of native plant species to resist or constrain invasion, restoration practitioners will need guidance on how to select species or genotypes (e.g. Crutsinger, Souza & Sanders 2008), planting densities, and revegetation methods to minimize invasive plant impacts.

SMALL-SCALE EXERIMENTS AND REAL-WORLD APPLICATION

Experiments are the only way to determine truly effective control methods. Results from plot-level or short-term empirical studies may not be effective or relevant when applied at the site or landscape level (Erskine Ogden & Rejmánek 2005; Flory 2010). If small-scale studies are not relevant to larger-scale application, then invasive plant control research has little utility for managers. Le Duc, Pakeman & Marrs (2003) reported that results from a study with a smaller plot size were less reliable compared to those sites with a larger plot size, probably due to a higher type II error when plot size was reduced. Very few ecological studies have explicitly tried to apply results from small-scale experiments to the landscape scale (but see Erskine Ogden & Rejmánek 2005; DiTomaso *et al.* 2006; for example). One insightful study took findings from a pilot study and applied the most successful control methods to the landscape scale (Erskine Ogden & Rejmánek 2005). As expected, cover of the invasive *Foeniculum vulgare* Mill. (fennel) was significantly reduced but, contrary to the pilot study, native species cover and richness did not improve after spraying and instead, an introduced annual grass dominated. We need to evaluate the scales at which different control methods are most appropriate (Pauchard & Shea 2006; Brown, Spector & Wu 2008) and examine relationships between research findings at small-scales and larger-scale implementation. Researchers can capitalize on large-scale control efforts like those conducted by weed control agencies to employ large-scale experiments (Rice & Toney 1998).

THE PRACTICALITIES OF SCALING UP CONTROL METHODS

Managers have varying responsibilities and resources, making some control methods more viable than others. One challenge for researchers is to evaluate techniques most relevant to managers, but many studies evaluate techniques that are not appropriate for large-scale application. For instance, a number of studies we reviewed employed hand removal of invasive plants, which might be possible when managing a small area or when labour resources are available (Albrecht *et al.* 2005), but hand removal is rarely feasible for managers. Similarly, soil amendments, such as sucrose or sawdust additions, have been employed to evaluate whether limiting excess nutrients can shift the competitive balance from invasives to natives (e.g. Morghan & Seastedt 1999; Huddleston & Young 2005; Iannone & Galatowitsch 2008). Unfortunately, the carbon amendments required to lower nutrient levels cannot be applied on large scales due to logistic and economic constraints. Such experimental results can be useful in identifying the mechanisms behind successful invasive plant control and can inform other potential management strategies. However, we caution researchers to consider the practicality of large-scale application of their control methods and to favour techniques that are economically and logistically feasible.

CONSIDERATION OF COSTS CAN IMPROVE THE USEFULNESS OF RESEARCH TO PRACTICE

Few studies gave consideration to control strategy costs and even fewer provided a quantitative assessment of treatment costs. Given that costs often drive restoration decisions, more researchers need to explicitly consider costs as part of their studies. This is particularly important given what researchers can afford to test and what managers have resources to implement. Sometimes the cheapest strategy is the least effective (e.g. burning; Musil, Milton & Davis 2005) and the most effective one is cost prohibitive (e.g. hand removal; Hewitt *et al*. 2005). In fact, researchers have found that commonly employed restoration treatments had little effect (e.g. spring glyphosate application for *Phalaris arundinacea* control; Reinhardt Adams & Galatowitsch 2006). Treatments may be frequently applied because of their convenience (labour availability) or low cost (herbicide over hand removal), regardless of effectiveness.

Researchers need to consider costs associated with effective and less-than-effective control methods so that managers can account for costs, in addition to logistics and effectiveness. A number of examples illustrate how researchers can incorporate cost considerations into their work; for example, some studies provide cost estimates per hectare for experimental treatments (Pickart *et al*. 1998; Paynter & Flanagan 2004; Musil, Milton & Davis 2005) or evaluate cost-effectiveness in terms of capital, personnel, time and total costs (Musil, Milton & Davis 2005; Meloche & Murphy 2006).

RESEARCH LIMITATIONS CAN BE ADDRESSED BY ADAPTIVE MANAGEMENT

Although invasive plant control research has improved management, our review highlights shortcomings that limit insight into the ultimate goal of ecosystem restoration. Linking research and restoration through adaptive management may address these limitations. Adaptive management involves partnerships of practitioners and scientists that assess treatment outcomes on a landscape scale, and increase knowledge of treatment effectiveness with models (Williams, Szaro & Shapiro 2009). Adaptive management naturally fosters cost effectiveness and practicality, and also improves understanding of stochastic influences on invasive plant management (e.g. the effect of annual climate variation on control outcomes). The focus therefore remains on the long-term objective of ecosystem restoration, rather than short-term changes, such as temporary decreases in invader abundance. Invasive plant control research could be well-served by this approach. Recent reviews have shown how combining experiments with restoration projects increases learning speed (Wagner *et al*. 2008; Palmer 2009).

Despite the advantages of adaptive management, in this review we saw no examples of application of adaptive management to invasive control, perhaps because invasive plant control efforts are often administratively separated from general ecosystem management (Foxcroft 2004). Authors found aspects of adaptive management advantageous to research, for instance choosing control methods with application to long-term objectives (Taylor & McDaniel 1998), and revising hypotheses following one round of experiments (Cummings *et al*. 2005). Some tried to incorporate invasive plant control research into restoration but were hindered by confounding factors (Reeder & Hacker 2004), a lack of replication (Huddleston & Young 2005), and compromised research resulting from reduced influence over experimental design (Cione, Padgett & Allen 2002). Working to overcome these barriers to utilize an adaptive management approach could broaden invasive plant research, taking a critical step toward identifying practical solutions.

Conclusion

Given the substantial ecological and financial impact invasive species can have, it is not surprising that invasive plant control is a primary restoration activity of land managers. They have the difficult task of controlling invasive species under financial and logistical constraints, and often considerable uncertainty regarding the outcome of control methods. Researchers play an important role in improving restoration practice. Our systematic review and meta-analysis highlighted common problems associated with control, including non-target effects with herbicide treatments and novel invasions following control. We also revealed important shortcomings in invasive plant control research, including minimal focus on native response, limited scope of research experiments, and incomplete evaluation of costs and benefits associated with an invasive species management plan. Considering the applications of research to invasive plant management during the experimental design phase, by involving practitioners and using an adaptive management approach, will make studies more effective. Others have noted how remarkably disconnected research can be from actual efforts to conserve and restore ecosystems by practitioners (Anonymous 2007; Hulme 2011); invasive plant researchers have a particular obligation to bridge this gap.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Papers included in the systematic review.

Table S1. Assumptions for meta-analysis data extraction.

Table S2. Species that were the subject of 3 or fewer papers included in the systematic review.

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