Invasive Plant Science and Management 2014 7:147–163

Effectiveness of Exotic Plant Treatments on National Park Service Lands in the United States

Scott R. Abella*

The United States created national parks to conserve indigenous species, ecological processes, and cultural resources unimpaired for future generations. Curtailing impacts of exotic species is important to meeting this mission. This synthesis identified 56 studies reported in 60 publications that evaluated effects of exotic plant treatments on National Park Service lands. Studies encompassed 35 parks in 20 states and one U.S. territory and included 157 exotic plant species. Eighty-seven percent of studies reported that at least one treatment reduced focal exotic species. Of 30 studies evaluating response of native vegetation, 53% reported that natives increased, 40% reported neutral responses, and 7% reported that natives decreased. For at least some of the neutral cases, neutrality was consistent with management objectives. In other cases, insufficient time may have elapsed to thoroughly characterize responses, or restoration might be needed. Nonfocal exotic species increased in 44% of the 16 studies evaluating them, but the other 56% of studies reported no increase. Results suggest that: (1) a range of exotic species spanning annual forbs to trees have been effectively treated; (2) developing effective treatments often required extensive experimentation and balancing nontarget impacts; (3) presence of multiple exotic species complicated treatment efforts, highlighting importance of preventing invasions; and (4) placing treatment objectives and outcomes in context, such as pretreatment condition of native vegetation, is important to evaluating effectiveness. Attaining the goal in national parks of conserving native species and ecological processes minimally influenced by exotic species will likely require comprehensive management strategies inclusive of treatment interactions with focal exotic species, other potential invaders, and native species.

Key words: Control, effects, nonnative species, vegetation, secondary invasion, response.

National parks in the United States were designated to conserve significant natural and cultural features unimpaired for future generations (Organic Act 1916). The 2006 National Park Service management directive reaffirmed the key objective of preserving indigenous biodiversity and ecological processes within parks unimpaired (National Park Service 2006). The 401 National Park Service units contain irreplaceable features and native species, often harboring the only locations where certain cultural sites and species occur (Shafer 2012). Invasions by exotic species increasingly threaten park resources and undermine the objective of conserving indigenous biodiversity and ecological processes within parks (Jenkins and Johnson 2008). For example, Allen et al. (2009) assessed 216 of the parks and reported that they contained a total of 3,756 exotic plant species. All parks contained exotic plants, with several individual parks containing over 400 exotic plant species. Not all exotic plants severely impact indigenous ecosystems, but effects of high-impact species already are evident and some current low-impact species have potential for severe impacts in the future (Gilbert and Levine 2013; Vilà et al. 2011). As one example of a severe impact, invasion by exotic plants in some parks has increased fuel loads and corresponded with increasing extent and severity of nonindigenous wildfire regimes (D'Antonio et al. 2011). These fires have devastated native communities ill adapted to the novel disturbance regime, in addition to impacting cultural resources and altering anthropogenic visitor experiences (Brisbin et al. 2013).

In response to threats posed by exotic plant invasions, the National Park Service, similar to many other conservation organizations, has initiated treatments seeking to reduce exotic plants while promoting native species (Fraley et al. 2007). Treatments encompass physical methods such as

DOI: 10.1614/IPSM-D-13-00058.1

* Ecologist, National Park Service, Washington Office, Natural Resource Stewardship and Science Directorate, Biological Resource Management Division, 1201 Oakridge Drive, Fort Collins, CO 80525. Current address: Natural Resource Conservation LLC, 1400 Colorado Street, Boulder City, NV 89005. Corresponding author's E-mail: abellaNRC@gmail.com

Management Implications

National parks in the United States are areas where a management goal is to conserve native species and processes free from influences of exotic species (National Park Service 2006). Meeting this goal in light of the approximately 4,000 exotic plant species (in addition to other types of exotic organisms) already present in parks will be challenging and require effective treatment strategies applied at different scales in comprehensive ecological and social frameworks. A systematic search of published literature uncovered 56 projects conducted on National Park Service lands in which effects of exotic plant treatments were assessed.

On one hand, results were encouraging in that most projects (87%) found at least one treatment reduced focal exotic species. Moreover, treatments negatively affected native vegetation in only two projects. There also were five projects reporting eradication of 1 to 21 species within parks and some examples of effective broad-scale treatments aligned with large-area infestations. On the other hand, < 4% of exotic plant species already present in national parks have had effects of treatments upon them evaluated on National Park Service lands. There also is little to no documented information on overall trends of exotic plant abundance for most parks (Allen et al. 2009). Priorities for increasing effectiveness of management interventions include evaluating treatment effects in a comprehensive ecosystem benefits/tradeoffs approach (Steers and Allen 2010), enhancing knowledge on species trends and impacts to facilitate prioritization of limited treatment resources (Vilà et al. 2011), continued development of single- and multi-species treatments that minimize undesired effects and are cost-effective (Lodge et al. 2006), improving early detection and treatment capacity (DiTomaso et al. 2007), and providing a treatment framework encompassing ecological restoration and climate change adaptation (Funk et al. 2009). Results further highlight importance of assessing treatment outcomes in context of the present condition of the ecological community, and against an appropriate benchmark relative to doing nothing which often should include unabated exotic species impacts. Recognizing that multiple treatment applications and time may be required for native species recovery, long-term, effective commitments to managing exotic species are needed for limiting degradation in national parks.

cutting, pulling, or fire; chemical methods including herbicides or application of carbon to stimulate soil microbes and reduce plant-available nutrients; or biological methods such as establishing native plant species to compete with exotics (Sheley et al. 2011).

Outcomes to vegetation of imposing treatments on an invaded ecosystem can take many forms contingent upon numerous factors (Harms and Hiebert 2006; Rinella et al. 2009; Steers and Allen 2010). A way to conceive treatment effects is to categorize responses of the focal exotic species, native species, and other exotic species as decreasing, neutral, or increasing. This results in 27 potential combinatorial responses. Native species might be unresponsive to treatment through numerous mechanisms, such as if the natives had not been reduced by the invasion (e.g., when exotics invade space unoccupied by plants); if insufficient time or events (e.g., moist or dry weather periods) occurred since treatment; or if the invasion, treatment itself, or new climatic regime might have somehow reduced native abundance to a lower baseline level (D'Antonio and Meyerson 2002; Hulme et al. 2013). On the other hand, treatments might increase native species if natives have been reduced and limited by the invasion, or through other mechanisms such as some beneficial aspect of the treatment (e.g., fire stimulating germination) that might hinge upon effects to focal exotic species (Pyšek et al. 2012). Conversely, treatments could decrease natives if the exotic was actually facilitating natives (e.g., exotics with N-fixing symbioses) or if the treatment has known or unknown impacts to native species (Rinella et al. 2009). Secondary invasion, by other exotic species after a focal exotic is removed, can negate treatment benefits or even worsen the situation if the removed invader is replaced by one more damaging (Kettenring and Adams 2011).

It is recognized that assessing treatment effectiveness, including reporting both successful and failed control efforts, is essential to advancing exotic plant management (Blossey 1999; Rinella et al. 2009). Resources for land management are limited and consequences of ineffective treatments or unanticipated nontarget effects can be substantial, making development of ecologically and cost-effective strategies paramount (Pimentel et al. 2005). In fact, Maxwell et al. (2009) concluded that dedicating 50% of time available for exotic plant management to well-done monitoring would not result in expansion of exotic populations (in comparison to expending 100% of time on treatment) because of gains in treatment efficiency.

There are some unique challenges for assessing effectiveness of a management intervention such as exotic plant treatment (Davis 2009). For a newly established, small population, for example, collecting temporally repeated pretreatment data to determine if the population might decline without treatment risks expansion to a full infestation. The most applicable assessment data in this eradication context might be a simple binary response of presence/absence of the species. Moreover, eradication is scale- and time-specific to a defined area (e.g., particular sites within a park or to a whole park) and time period, as future introductions can necessitate further eradication attempts (Ransom et al. 2012). It also may not be justifiable to leave untreated areas as controls, for reasons such as legal requirements to protect a rare native species. As a result, before–after or treated–never invaded comparisons are important in study designs of exotic plant treatment effectiveness (Kettenring and Adams 2011). For land management purposes, practitioners are often comfortable knowing correlations between treatments and outcomes when cause–effect statistical designs are not feasible or ethical (Reid et al. 2009). These examples illustrate that several study designs and response data are applicable to evaluating treatment effectiveness.

The objective of this work was to synthesize effects of exotic plant treatments on focal exotic plant species, native species, and nonfocal exotic species on U.S. National Park Service land. The National Park Service manages 32 million ha (79 million ac) distributed across 401 parks in all 50 U.S. states and two U.S. territories. A significant portion of the United States' natural and cultural resources are represented by these units, and they are visited by over 280 million people annually. It is increasingly recognized that conserving these resources in accordance with the National Park Service mission requires curtailing exotic species impacts (National Park Service 2006).

Materials and Methods

Published literature regarding exotic plant treatments on National Park Service land was obtained using defined search procedures and criteria for including an article. The following resources were searched: article databases since inception through 2012 of Google Scholar, AGRICOLA, JSTOR, and BioOne (including journals such as *Invasive Plant Science and Management* and *Natural Areas Journal* regularly publishing exotic plant articles); the individual journals *Restoration Ecology*, *Ecological Restoration*, *Biological Invasions*, and *Journal of Applied Ecology*; and the National Park Service's article database, Integration of Resource Management Applications (http://science.nature.nps.gov/im/datamgmt/irma.cfm). Article titles, abstracts, and key words were searched for the following terms: exotic, nonnative, nonindigenous, plant, vegetation, species, treatment, management, control, effectiveness, assessing, assessment, monitoring, National Park Service, preserve, monument, and historic site. Reference lists of located articles were also examined for relevant articles.

Criteria for inclusion of a study in the quantitative synthesis included that it (1) be conducted on one or more of the 401 units of the National Park Service, (2) be published (as a journal article, book chapter, conference proceedings, or other published outlet), and (3) report extractable data on management interventions aimed at reducing abundance of one or more vascular exotic plant species in terrestrial habitat. Only published or in-press literature was included because little unpublished literature on treatment effects was available, key details on treatment methods and sampling were often absent from unpublished literature, and the unpublished work was rarely available online or widely accessible. The criterion for reporting extractable data required that data on one or more focal exotic species be reported or that exotic species could be separated out from native species and be presented as either quantitative (e.g., biomass of a species) or categorical data (e.g., presence/absence for eradication attempts). Only studies evaluating in situ plant communities were included, excluding some studies such as those by Haubensak and D'Antonio (2006) and Abella et al. (2012) performed within parks but examining treatment effects on experimentally seeded exotic plants or in created common gardens.

For each article meeting inclusion criteria, data were extracted from the article text, tables, or figures and entered into a database. A statistical meta-analysis was considered but was not performed because data reported in studies took numerous forms (including presence/absence), and study designs varied substantially from before/after or control/impact to full factorial designs including pretreatment data with controls. As a result, data were summarized according to original measures reported in an article, as derived counts of the number of treated species (e.g., number of species eradicated based on absence data), or as calculated averages such as for presenting overall exotic plant community abundance in addition to individual exotic species. Native/exotic status to the Pacific Islands and lower 48 states and growth form classification followed the Natural Resources Conservation Service (2013). The number of studies that reported reductions, no change (neutral), or increases in the focal exotic species, native species, and other exotic species was compiled. The reduced, neutral, or increase responses were categorized based on the longest-term data reported in articles and on measures including statistical significance (or lack thereof) or means of responses and presence/absence of a focal exotic in eradication. Cover was used as the response whenever it was reported; otherwise, plant density or other measures were used.

Results and Discussion

Description of the Literature. Fifty-six studies, reported in 60 publications between 1984 and 2013, evaluated exotic plant treatments on National Park Service lands (Appendix 1). Studies encompassed 35 national park units in 20 states and one U.S. territory. Parks with the most studies included Hawaii Volcanoes National Park (seven studies), and with four studies each, Everglades National Park (Florida), Big Cypress National Preserve (Florida), Channel Islands National Park (California), and Lake Mead National Recreation Area (Arizona–Nevada). The vegetation types of desert, shrubland, prairie, wetland, and forest were all represented in the studies. Treatments evaluated included herbicide, cutting, girdling, mowing, clearing (soil or sod removal), controlled grazing, prescribed burning, solarization, fertilizing native species, covering (with fabric to limit plant emergence), carbon addition (to reduce nutrient availability), and planting or seeding competitive native species. There were 157 focal exotic species evaluated, with 72 (46%) of these assessed

https://doi.org/10.1614/IPSM-D-13-00058.1 Published online by Cambridge University Press

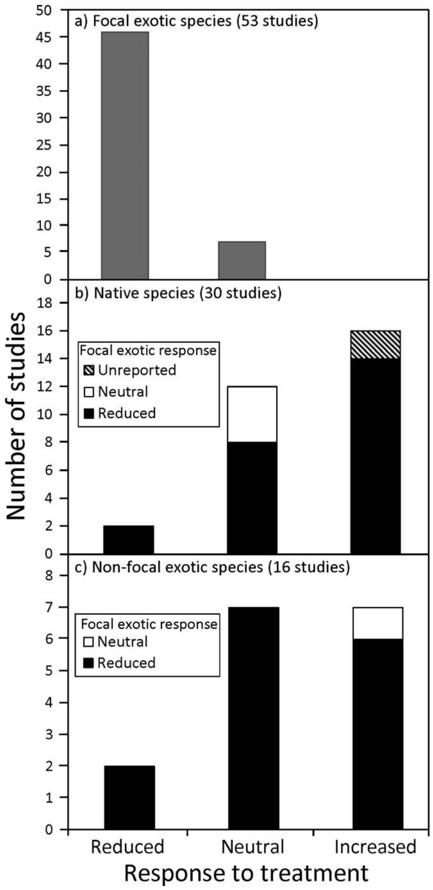

Figure 1. Summary of responses of (a) focal exotic plant species, (b) native species, and (c) nonfocal exotic species to exotic plant treatments on National Park Service lands in the United States. For response of (b) native and (c) nonfocal exotic species, response of the focal exotic species to treatment is cross-tabulated. In (b), for example, the focal exotic species was reduced by treatment in 8 of the 12 studies where native species displayed a neutral response to treatment of the focal exotic.

only in Hawaiian parks. Species were distributed according to the following growth forms: 34 trees (22% of the total 157 species), 23 shrubs (15%), 65 forbs (41%), five vines (3%), and 30 graminoids (19%). Life spans of the species included 11 annual (7%), two annual–biennial (1%), eight biennial (5%), 13 annual–perennial (8%), six biennial–perennial (4%), and 117 perennial (75%). The number of focal exotic species evaluated in a study ranged from 1 (62% of studies) to 62 species (Tunison 1992).

Fifty-three (95%) of the 56 studies reported data on a focal exotic plant, and the remaining three studies reported only native species. Thirty (54%) of the studies evaluated native species, and 16 studies (29%) evaluated exotic species other than the focal exotic species. Twenty-nine (52%) studies collected some pretreatment data, which included recording presence of an exotic species before treatment in an eradication context of small populations. Twenty-five (45%) studies compared treatments within their study, and seven studies evaluated effects of timing of treatment. Studies evaluated responses from < 1 to 12 yr after treatment, with a median of 3 yr.

Treatment Effects. Most studies reported that at least one treatment within a study reduced focal exotic species (Figure 1a). About half of studies reported increases in native species (Figure 1b). No response or reductions in other (nonfocal) exotic species occurred in 56% of studies, with the remaining 44% reporting increases (Figure 1c). Treatment effects on focal exotic, native, and other exotic species are discussed in the following sections.

Focal Exotic Species. Five studies were conducted in an eradication context where populations of focal exotic species were small and geographically restricted (Abella et al. 2009; Dalrymple et al. 2003; Tunison 1992; Tunison and Zimmer 1992; Whipple 2001). Studies reported that between 1 and 21 species were eradicated from an area within a park or entire park, at least at the time of the study, recognizing that future introductions could occur. Eradication treatments included hand-pulling, herbicide, cutting, or a combination of these. Populations of up to several hundred plants and 1 ha were eradicated. The ≤ 1-ha size of eradicated populations was smaller than the 1-ha cutoff, below which Rejmánek et al. (2005) reported eradications were most economical.

Considering all studies including the eradication studies, at least one treatment within a study reduced focal exotic species in 46 of 53 studies (87%) reporting data on focal exotics (Figure 1a). The remaining seven studies (14%) reported no effect. The three studies that did not report on a focal exotic were conducted in a context where it was likely that the focal exotic had been eliminated or sharply reduced, and only responses of native species were evaluated (Bay and Sher 2008; D'Antonio et al. 1998; Hughes and Vitousek 1993). With few exceptions, the seven studies that reported neutral effects on the focal exotic species either facilitated identifying future treatments that could reduce the focal exotic or still achieved some partial resource benefit. For example, Doren et al. (1991) found that prescribed fire did not reduce Brazilian peppertree (*Schinus terebinthifolius* Raddi) in Everglades National Park, but these findings led to testing and development of more intensive clearing treatments that did reduce *Schinus* (Dalrymple et al. 2003). In another example, Tyser et al. (1998) found no overall effect of spraying the herbicide clopyralid along roadsides of Glacier National Park because increases in exotic graminoids offset reductions in exotic forbs. This suggested, however, potential for combining herbicide regimes effective for both broad-leaf and grass plants, coupled with seeding of native species, which promoted native community establishment.

Potential publication bias warrants consideration (Møller and Jennions 2001), such as a possibility of studies that did not find significant reductions in focal exotic species being least preferentially published. Seven studies did not report significant reductions; there were many examples reported of unsuccessful treatments within the 46 studies that did report at least one successful treatment, and there also was reporting of treatments that increased other exotic species. Consequently, there was no evidence of exclusive reporting of successful treatments. It is important to report both perceived successes and failures to provide a balanced view of treatment effectiveness. Eventual control of several species such as *Schinus terebinthifolius* and melaleuca [*Melaleuca quinquenervia* (Cav.) S.F. Blake] in Florida parks resulted from learning from ineffective treatments (Dalrymple et al. 2003).

Native Species. Of 30 studies reporting responses of native species to exotic plant treatments, most studies (16 studies, 53%) reported that natives increased, but a substantial portion (12 studies, 40%) reported that natives were not affected (Figure 1b). Two studies (7%) reported that natives decreased, despite finding that treatments had reduced the focal exotic species. In one of the studies, in prairies at Lyndon B. Johnson National Historical Park in Texas, Simmons et al. (2007) found that none of the suites of treatments (herbicide, fire, and mowing) consistently increased native species 1 yr after treatment. These authors were dealing with an aggressive exotic perennial grass, yellow bluestem [*Bothriochloa ischaemum* (L.) Keng], and a short study duration, and called for future testing of timing of treatment. On burned sites in Zion National Park, Fuhrmann et al. (2009) found that native species richness was greater on untreated areas than on areas that had received herbicide plus seeding of natives. It is important to note, however, that treatments did reduce biomass per plant by 75% of the focal exotic species foxtail brome (*Bromus madritensis* L.) and downy brome (*Bromus tectorum* L.). Reducing exotic grass fuel loads that facilitate novel fire regimes is a primary management goal in American Southwest arid lands where the study was conducted (Brisbin et al. 2013).

In 33% of the 12 studies where treatments did not affect native species, treatments also had no measurable effect on focal exotic species. In contrast, 14 of the 16 studies (88%) reporting beneficial treatment effects on natives found that the treatments reduced focal exotic species. The other two studies did not quantitatively report treatment effects on focal exotic species, but reductions in focal exotics were apparent (D'Antonio et al. 1998; Hughes and Vitousek 1993).

Although the data suggest that treatments overall more frequently reduced focal exotic species than they increased native species, native species did increase in 53% of studies. Among examples of native species increases, exotic plant treatment along Lake Michigan sand dunes in Sleeping Bear Dunes National Lakeshore both increased native plant density and enhanced pollination of the federally threatened sand dune thistle [*Cirsium pitcheri* (Torr. ex Eaton) Torr. & A. Gray] (Baskett et al. 2011). In tropical forests of National Park of American Samoa, Hughes et al. (2012) found that 6 yr after girdling the exotic tree peacocksplume [*Falcataria moluccana* (Miq.) Barneby & Grimes], forest community biomass was dominated (95%) by native species.

In studies where native species were unaffected by treatments, it is important to recognize that this neutral response of native species to removal of an exotic might sometimes be desired by managers. In Saguaro National Park in Arizona, for example, removing the perennial buffelgrass [*Pennisetum ciliare* (L.) Link] resulted in native communities indistinguishable from those of never-invaded areas 1 to 4 yr after treatment (Abella et al. 2013a). *Pennisetum* dramatically increases fuel loads and fire risk in these Sonoran Desert ecosystems where fires were not a major part of the evolutionary environment of the native species. The study suggested that the goal of reducing fire risk could be achieved without impacting the native community. An increase in native community measures would not necessarily have been desirable if the treatments resulted in increases of early colonizing native species, as instead the park seeks to conserve mature cactus–shrub communities (Abella et al. 2013a).

Nonfocal Exotic Species. A major concern in exotic plant management is that other exotic species, sometimes even more damaging to native species, simply replace a focal exotic species that was removed (Moyes et al. 2005). Of 16 studies reporting data on treatment effects on nonfocal exotics, nine studies (56%) reported neutral effects or reductions to nonfocal exotics (Figure 1c). The focal exotic species was reduced in all nine studies reporting neutral effects or reductions for other exotics, suggesting that secondary invasion by other exotics did not occur or that other exotic species already present did not increase. Seven studies (44%) found that nonfocal exotics increased. In six of those, the focal exotic was reduced, suggesting secondary invasion. Moyes et al. (2005), working in Santa Monica Mountains National Recreation Area in California, provided a dramatic example where prescribed fire resulted in type conversion from exotic annual grassland dominated by ripgut brome (*Bromus diandrus* Roth) to monoculture of the exotic annual forb black mustard [*Brassica nigra* (L.) W.D.J. Koch]. In another example, Love and Anderson (2009) found that treatments that reduced the exotic shrub Morrow's honeysuckle (*Lonicera morrowii* A. Gray) increased several other exotics in old fields at Fort Necessity National Battlefield in Pennsylvania. These authors concluded that treatments effective on the focal species would need to be coupled with treatments for the nonfocal exotics and potentially with planting native species.

Treatment Type, Timing, and Frequency. The variables of type, timing, and frequency of treatment were often important to outcomes in studies that examined these variables. In Shenandoah National Park of Virginia, for example, Burch and Zedaker (2003) found that six different herbicides applied to uncut stems all similarly induced 98 to 100% mortality of tree-of-heaven [*Ailanthus altissima* (Mill.) Swingle]. Cutting the trees, however, only induced 21% mortality and stimulated sprouting. A similar response is observed in the exotic *Tamarix* spp. in American Southwest arid lands where cutting simply promotes sprouting unless herbicide is immediately applied to stumps (Harms and Hiebert 2006). Illustrating the importance of combining treatment types, Daehler and Goergen (2005) reported that prescribed burning coupled with herbicide optimally reduced *Pennisetum ciliare*, while increasing native species at Puukohola Heiau National Historic Site in Hawaii. Faulkner et al. (1989) showed importance of treatment timing, where fall burns increased one focal exotic species (Chinese privet [*Ligustrum sinense* Lour.]) while decreasing another (Japanese honeysuckle [*Lonicera japonica* Thunb.]). Winter burns reduced both species. In another example, Abella et al. (2013b) found that pulling and herbicide both reduced germination when applied early in rosette development in the exotic annual African mustard (*Brassica tournefortii* Gouan) in the Mojave Desert at Lake Mead National Recreation Area, whereas only herbicide prevented germinable seed when plants were fully developed. In some examples where timing was unimportant, such as Snyder's (1999) finding that cutting during any month never induced mortality $> 8\%$ for *Melaleuca quinquenervia* in Florida's Big Cypress National Preserve, the treatment type was ineffective regardless of timing. Illustrating importance of frequency of treatment, Alexander and D'Antonio (2003) found that at least three prescribed burns were required to reduce exotic shrubs and promote native species at Point Reyes National Seashore in California. Results underscore that optimally selecting treatment type, timing, and frequency are critical to achieving effectiveness, and combinations of treatments or multiple applications can be necessary.

Although studies in this synthesis reinforced principles of invasive plant management highlighting importance of type, timing, and frequency of treatments (Flory and Clay 2009), results also suggested that extensive experimentation was often needed to identify effective treatments. Although some general principles on treatment regimes exist for some related groups of species, effective treatments often are identified on an individual species basis owing to diversity in species traits and the often individualistic responses of species and sites (Sheley et al. 2011). Treatment protocols exist for killing some major exotic species such as *Tamarix* spp., but even for these species, more remains to be learned about optimizing treatments to meet other objectives such as promoting natives and reducing invasion by other exotic plants (Harms and Hiebert 2006). There remains a need to assess effects of a range of treatment alternatives not only on focal exotic species, but also on impacts of treatments and removal of the exotic on the rest of the ecosystem (Brown et al. 2008). This task is particularly complicated when multiple focal exotic species exist in an area and differ in their traits. However, the finding of this review—that 87% of studies identified at least one effective treatment on a focal exotic species, and only two studies reported that native plants were overall negatively affected—is encouraging.

Species Amenability to Treatment. Thirty-four (61%) studies focused on only one focal exotic species, whereas 22 (39%) studies evaluated more than one species, including communities dominated by many exotic species. In comparing species across studies that were examined in more than one study and in comparing species within multi-species studies, no overall trends were evident for differential amenability to treatment among plant groups (e.g., annual vs. perennial, forb, or shrub). Additionally, in some of the examples where particular exotic species were affected more than others by treatment within a multi-species study, this could vary among treatment types (e.g., Choi and Pavlovic 1998). In Hawaii Volcanoes National Park, Santos et al. (1992) illustrated how seven priority species could be individually controlled through development of reliable species-specific treatment protocols. The 56 studies collectively highlighted that many plant growth forms have been reduced by treatments on National Park Service lands.

Site, Landscape, and Temporal Perspectives. Most studies were conducted at a site or collection of sites, with few studies examining effects of treatments at a landscape scale. This should be kept in context where in many cases, such as in an eradication context where a species might only occupy one small site, the scale and spatial extent of studies were aligned with the scale of exotic plant occurrences. In an eradication context in addition to other situations, however, surveying or monitoring across larger areas can increase inference regarding treatment effectiveness. Moreover, invasions in many parks are extensive such that results of treatment effects at one site are not necessarily informative for how feasible or effective treatments are at landscape scales. Although parks often have specific high-priority sites (e.g., sites containing rare native species or anthropogenic visitor services), ultimately the mission of the National Park Service of conserving indigenous ecosystems applies to entire parks. This makes understanding treatment effectiveness across landscapes important.

There were some examples of landscape-scale assessments of treatment effects. Big Cypress National Preserve and Everglades National Park in Florida have conducted landscape-scale clearing of the exotic trees *Schinus terebinthifolius* and *Melaleuca quinquenervia*. Pernas and Snyder (1999), for instance, reported that 48,000 ha of *Melaleuca* existed in Big Cypress in 1992, but after 5 yr of treatment, the infestation extent was reduced by 60% to 19,000 ha. In Gateway National Recreation Area near New York City, Greller et al. (2000) used a vegetation mapping approach to measure the proportion of the landscape covered by Japanese knotweed (*Polygonum cuspidatum* Siebold & Zucc.). Before treatment, *Polygonum* vegetation occupied 4.5% of the 579-ha study landscape compared to 5.1% after 7 yr of mowing treatments. Greller et al. (2000) discussed difficulty with their assessment approach regarding mapping of the *Polygonum* vegetation type, however, as they noted that density of *Polygonum* within patches had been sharply reduced even if the perceived map cover had increased. In a more recent example, Ransom et al. (2012) used a reproducible mapping approach with defined criteria for designating points and polygons to map cover of 21 exotic species on two areas, each of 648 ha in Dinosaur National Monument of Utah. One to 5 yr after several treatments, area infested by 15 of the exotic species was sharply reduced, but the study also illustrated importance of treating new invaders following initial treatments.

Several considerations are important to understand how well results of treatments applied at fine scales (such as the $<$ 0.1-ha plots often used) correspond with treatments applied to broader areas. First, treatment application procedures might need to differ between small and large areas. For example, small areas can be treated by manual methods such as backpack-spraying of herbicide, but larger areas can require different methods such as herbicide application by helicopter (Brisbin et al. 2013). This could affect treatment outcomes, as, for example, precision in location of treatment application might decrease when moving from small to large areas. Second, when spatial heterogeneity is high or treatment outcomes are scale-specific such as for species richness, size of sampling unit can influence perception of treatment effects (Kettenring and Adams 2011). The study by Erksine Ogden and Rejmánek (2005) was one of the few to discuss feasibility of extrapolating treatments applied on small areas to larger areas. These authors reported that general trends in exotic fennel (*Foeniculum vulgare* Mill.) and native species cover were similar between the small and large treated areas, but there were differences detected between the small and large areas in temporal fluctuations. This could result from many factors, such as large areas containing more diverse soil moisture regimes than smaller areas, which could affect perceptions of temporal vegetation fluctuations related to weather.

As is well-documented in invasive plant science (Kettenring and Adams 2011), the short duration of most studies hinders understanding potential longer-term vegetation dynamics posttreatment. Even within the short-duration posttreatment assessment period (typically $<$ 4 yr), some studies reported that the specific year in which measurements were made could affect perception of treatment effects or that there were temporal gradients in vegetation responses (Choi and Pavlovic 1998). If exotic plant invasion, treatment, and removal is viewed as a disturbance, it may be unsurprising that some studies did not report recovery of native species within the few-year measurement period posttreatment. In desert parks, for example, recovery of native desert vegetation from disturbance can require decades to centuries and hinge upon presence of infrequent years favorable for plant establishment (Abella 2010). The longest posttreatment assessment of any study was 12 yr. That study was conducted in the Mojave Desert and found that posttreatment communities were dominated by native species but at lower abundance than noninvaded reference communities (Bay and Sher 2008). Short funding duration and personnel turnover hinder longer-term assessments in exotic plant science, similar to other fields of science (Kettenring and Adams 2011). In addition to trying to overcome these barriers to extend monitoring periods, one way to expand generality of results of retrospective studies is to measure multiple years or account for extreme events to avoid the assumption that a single measurement year is representative (Diez et al. 2012). It is important to note, however, that short-term results can be extremely informative in exotic plant management for adjusting treatments, such as when unacceptable outcomes of initial treatments are immediately revealed (e.g., stimulation of sprouting or expansion of species).

Comparison to other Syntheses. Findings of this synthesis are partially consistent with findings of two recent syntheses of exotic plant removal: the review by Reid et al. (2009) of treatment effects on 20 priority weeds in Australia and Kettenring and Adams's (2011) global review of effects of exotic plant removal. All three syntheses highlighted the short duration of studies, which had a median of 3 yr in the present synthesis, 2 yr (range $<$ 1 to 8 yr) in Reid et al. (2009), and in Kettenring and Adams (2011), $\leq$ 2 yr for 75% of studies. Concern of other exotic species simply replacing treated exotic species was noted in all three syntheses: 44% of studies that evaluated this in the present synthesis, about 39% in Reid et al. (2009), and about 25% in Kettenring and Adams (2011). It should not be overlooked, however, that all three syntheses found incidence of this "secondary invasion" in fewer than 50% of studies, at least during the short posttreatment periods of the studies. The present synthesis found that study distribution among vegetation types was more balanced and had greater representation of deserts (16% of studies) than that of Kettenring and Adams (2011), who reported that studies were dominantly in grasslands (39% of studies), with only 1% in deserts. A greater percentage of papers evaluated native species responses to treatments in this synthesis (54%) than in either Reid et al. (2009; 19%) or Kettenring and Adams (2011; 42%). Moreover, this synthesis uncovered greater overall evidence of native species increases after treatments than reported by either previous synthesis. This could potentially relate to better overall ecological condition of U.S. national parks (among the highest protected status in the United States) compared to other types of land units. Reid et al. (2009) concluded that selecting sites for treatment that have some existing good-quality native vegetation may increase treatment effectiveness, and this situation would generally characterize U.S. parks.

Future Context of Treatments on National Park Lands. Results of this study help provide broad context for making future progress in exotic plant management and assessment on National Park Service and similar conservation landscapes. First, emphasizing promotion and assessment of broader functions and ecosystem responses after treatment beyond focal exotic species is a growing thrust in exotic species science (Brown et al. 2008). Exotic plant treatments and removal can affect many ecosystem components and functions. Evaluations of functional effects of exotic plant removal such as was done on pollination ecology of a rare plant species at Sleeping Bear Dunes National Lakeshore have potential for evaluating comprehensive tradeoffs and benefits of exotic plant treatment (Baskett et al. 2011). Second, it should be noted, however, that studies focused solely on developing control techniques for specific invaders will likely remain critical. This synthesis found that treatment effects on 157 exotic species have been reported, but Allen et al. (2009) found that at least 3,756 exotic plant species infest U.S. national parks. Although treatment protocols for some exotic species can be gleaned from literature on other lands, the fact that treatment effects have been evaluated on $< 4\%$ of plant invaders already in national parks is sobering. Third, it is important to have a realistic baseline against which to evaluate treatment effects. Nontarget treatment effects on native species, for example, is a concern, yet negative treatment effects on native plants were only reported in two studies (Fuhrmann et al. 2009; Simmons et al. 2007). Even with some undesired treatment effects, these effects might be far less severe than consequences of doing nothing. In the many western and Hawaiian parks where invasion by exotic grasses augmented fuel load and altered fire regimes, the benchmark against which to compare treatment effects should include burned landscapes where mature native ecosystems and cultural features are destroyed (Brisbin et al. 2013).

Fourth, some studies suggest that presence of multiple exotic species on a site (rather than a single species) complicates exotic plant management (e.g., Alexander and D'Antonio 2003). Multiple species can necessitate multiple treatment types, including different application timings, increasing treatment costs (Sheley et al. 2011). In some parks, such as California grassland parks dominated by exotic plants, simply having treatments maintain native plants as a component of the vegetation might be a reasonable goal (Moyes et al. 2005). These observations reinforce a major principle of exotic plant science that, where feasible, prevention and early treatment of new invaders to reduce the number of invaders to control is likely a most cost- and ecologically effective strategy (DiTomaso et al. 2007). Minimizing the number of invaders in a park might also reduce chance of secondary invasion of other exotics replacing a treated exotic. Fifth, similar to findings of Kettenring and Adams (2011), assessments of financial costs or resources required to implement treatments were rare (e.g., Love and Anderson 2009). While understanding ecological effectiveness might be a key first step to understand which treatments are viable, studies comparing costs and feasibility of a range of ecologically acceptable treatments would be valuable (Lodge et al. 2006).

Sixth, framing treatments within an ecological restoration and climate change adaptation context warrants further consideration. Application of ecological restoration, such as restoring indigenous fire regimes to naturally frequent-fire ecosystems, can create a management conundrum where restoration treatments are now conducted in ecosystems containing exotic plants (DiTomaso et al. 2006). Fire can increase some exotic plants (Keeley 2006), and efficacy of prescribed fire for reducing exotics and promoting natives was mixed in the few studies that evaluated fire in the present synthesis (e.g., Faulkner et al. 1989). Moreover, as suggested by other authors (Kettenring and Adams 2011), effects of invasions and exotic plant removal could be viewed as a disturbance following which native species might benefit from assisted recovery through restoration (Funk et al. 2009). As evaluations of the ethics and feasibility of potential climate change adaptation strategies in conservation areas continue, removing exotic species as a stressor to help facilitate adaptation of native communities to climate change is a potentially beneficial management strategy (Morales and Traveset 2009). In some parks, exotic species removal might be one of the only ethical and feasible climate change adaptation strategies available. It also is possible that climate change will actually create opportunities for reducing exotic species while promoting natives (Bradley and Wilcove 2009). Furthermore, effectiveness of treatments can change as exotic plants evolve, native communities change, and climates shift (Davis 2009).

Seventh, in some contexts it should be recognized that a finding that native species have a neutral response to treatment might concur with management goals. Many earlier studies and reviews have apparently assumed that native species have decreased as a result of invasion (Kettenring and Adams 2011; Reid et al. 2009). This is often, but not always, the case (Pyšek et al. 2012). In Saguaro National Park, Abella et al. (2013a) provided an example where native species had not necessarily decreased, removal of the exotic resulted in a native plant community indistinguishable from noninvaded areas, and the removal eliminated the exotic grass fuel load that posed significant fire hazard. In that study, the goal was to maintain mature desert shrubland, and increases in native measures such as species richness through an influx of early colonizing species would not have been desirable. These observations suggest that response of the native community should be placed in context of management objectives and that sometimes a "neutral" response of natives to exotic plant removal is desirable.

Acknowledgments

The authors of Choi and Pavlovic (1998), Alexander and D'Antonio (2003), Harms and Hiebert (2006), Bay and Sher (2008), Wolf (2008), Fuhrmann et al. (2009), and Brisbin et al. (2013) are gratefully acknowledged for providing raw data or correspondence regarding their data sets. Sharon Altman formatted Figure 1 and Appendix 1. Peter Budde, the Associate Editor, and two anonymous reviewers provided helpful comments on the manuscript. This paper is a contribution of the Natural Resource Stewardship and Science Directorate, National Park Service, of the U.S. Government. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Literature Cited

Abella SR (2010) Disturbance and plant succession in the Mojave and Sonoran deserts of the American Southwest. Int J Environ Res Public Health 7:1248–1284

Abella SR, Chiquoine LP, Backer DM (2013a) Soil, vegetation, and seed bank of a Sonoran Desert ecosystem along an exotic plant (*Pennisetum ciliare*) treatment gradient. Environ Manag 52:946–957

Abella SR, Craig DJ, Smith SD, Newton AC (2012) Identifying native vegetation for reducing exotic species during the restoration of desert ecosystems. Restor Ecol 20:781–787

Abella SR, Spencer JE, Hoines J, Nazarchyk C (2009) Assessing an exotic plant surveying program in the Mojave Desert, Clark County, Nevada, USA. Environ Monit Assess 151:221–230

Abella SR, Suazo AA, Norman CM, Newton AC (2013b) Treatment alternatives and timing affect seeds of African mustard (*Brassica tournefortii*), an invasive forb in American Southwest arid land. Invasive Plant Sci Manag. 6:559–567

Alexander JM, D'Antonio CM (2003) Control methods for the removal of French and Scotch broom tested in coastal California. Ecol Restor 21:191–198

Allen JA, Brown CS, Stohlgren TJ (2009) Non-native plant invasions of United States national parks. Biol Invasions 11:2195–2207

Baskett CA, Emery SM, Rudgers JA (2011) Pollinator visits to threatened species are restored following invasive plant removal. Int J Plant Sci 172:411–422

Bay RF, Sher AA (2008) Success of active revegetation after *Tamarix* removal in riparian ecosystems of the southwestern United States: a quantitative assessment of past restoration projects. Restor Ecol 16: 113–128

Blossey B (1999) Before, during and after: the need for long-term monitoring in invasive plant species management. Biol Invasions 1: 301–311

Bradley BA, Wilcove DS (2009) When invasive plants disappear: transformative restoration possibilities in the western United States resulting from climate change. Restor Ecol 17:715–721

Brisbin H, Thode A, Brooks M, Weber K (2013) Soil seedbank responses to postfire herbicide and native seeding treatments designed to control *Bromus tectorum* in a pinyon–juniper woodland at Zion National Park, USA. Invasive Plant Sci Manag 6:118–129

Brown CS, Anderson VJ, Claassen VP, Stannard ME, Wilson LM, Atkinson SY, Bromberg JE, Grant TA, Munis MD (2008) Restoration ecology and invasive plants in the semiarid West. Invasive Plant Sci Manag 1:399–413

Burch PL, Zedaker SM (2003) Removing the invasive tree *Ailanthus altissima* and restoring natural cover. J Arboric 29:18–24

Choi YD, Pavlovic NB (1998) Experimental restoration of native vegetation in Indiana Dunes National Lakeshore. Restor Ecol 6: 118–129

Daehler CC, Goergen EM (2005) Experimental restoration of an indigenous Hawaiian grassland after invasion by buffel grass (*Cenchrus ciliaris*). Restor Ecol 13:380–389

Dalrymple GH, Doren RF, O'Hare NK, Norland MR, Armentano TV (2003) Plant colonization after complete and partial removal of disturbed soils for wetland restoration of former agricultural fields in Everglades National Park. Wetlands 23:1015–1029

D'Antonio CM, Hughes RF, Mack M, Hitchcock D, Vitousek PM (1998) The response of native species to removal of invasive exotic grasses in a seasonally dry Hawaiian woodland. J Veg Sci 9:699–712

D'Antonio CM, Hughes RF, Tunison JT (2011) Long-term impacts of invasive grasses and subsequent fire in seasonally dry Hawaiian woodlands. Ecol Appl 21:1617–1628

D'Antonio C, Meyerson LA (2002) Exotic plant species as problems and solutions in ecological restoration: a synthesis. Restor Ecol 10: 703–713

Davis MA (2009) Invasion Biology. New York: Oxford University Press. 288 p

Diez JM, D'Antonio CM, Dukes JS, Grosholz ED, Olden JD, Sorte CJB, Blumenthal DM, Bradley BA, Early R, Ibáñez I, Jones SJ, Lawler JJ, Miller LP (2012) Will extreme climatic events facilitate biological invasions? Front Ecol Environ 10:249–257

DiTomaso JM, Brooks ML, Allen EB, Minnich R, Rice PM, Kyser GB (2006) Control of invasive weeds with prescribed burning. Weed Technol 20:535–548

DiTomaso JM, Enloe SF, Pitcairn MJ (2007) Exotic plant management in California annual grasslands. Pages 281–296 *in* Stromberg MR, Corbin JD, D'Antonio CM, eds. California Grasslands: Ecology and Management. Berkeley, CA: University of California Press

Doren RF, Whiteaker LD, Larosa AM (1991) Evaluation of fire as a management tool for controlling *Schinus terebinthifolius* as secondary successional growth on abandoned agricultural land. Environ Manag 15:121–129

Erksine Ogden JA, Rejmánek M (2005) Recovery of native plant communities after the control of a dominant invasive species, *Foeniculum vulgare*: implications for management. Biol Conserv 125:427–439

Faulkner JL, Clebsch EEC, Sanders WL (1989) Use of prescribed burning for managing natural historic resources in Chickamauga and Chattanooga National Military Park, USA. Environ Manag 13:603–612

Flory SL, Clay K (2009) Invasive plant removal method determines native plant community responses. J Appl Ecol 46:434–442

Fraley N, Furqueron C, Pernas T, Worsham E (2007) The National Park Service's exotic plant management teams in the Southeast and Caribbean. Nat Areas J 27:232–235

Fuhrmann K, Weber K, Decker C (2009) Restoring burned areas at Zion National Park (Utah). Ecol Restor 27:132–134

Funk JL, Cleland EE, Suding KN, Zavaleta ES (2009) Restoration through reassembly: plant traits and invasion resistance. Trends Ecol Evol 23:695–703

Gilbert B, Levine JM (2013) Plant invasions and extinction debts. Proc Natl Acad Sci USA 110:1744–1749

Greller AM, Durando C, Marcus LF, Wijesundara DSA, Byer MD, Cook R, Tanacredi JT (2000) Phytosociological analysis of restored and managed grassland habitat within an urban national park. Urban Ecosystems 4:293–319

Harms RS, Hiebert RD (2006) Vegetation response following invasive tamarisk (*Tamarix* spp.) removal and implications for riparian restoration. Restor Ecol 14:461–472

Haubensak KA, D'Antonio CM (2006) Restoration of a coastal California grassland after invasion by nitrogen-fixing shrubs, French broom and Scotch broom. Ecol Restor 24:93–99

Hughes F, Vitousek PM (1993) Barriers to shrub reestablishment following fire in the seasonal submontane zone of Hawai'i. Oecologia 93:557–563

Hughes RF, Uowolo AL, Togia TP (2012) Recovery of native forest after removal of an invasive tree, *Falcataria moluccana*, in American Samoa. Biol Invasions 14:1393–1413

Hulme PE, Pyšek P, Jarošík V, Pergl J, Schaffner U, Vilà M (2013) Bias and error in understanding plant invasion impacts. Trends Ecol Evol 28:212–218

Jenkins MA, Johnson KD (2008) Exotic plant species invasion and control in Great Smoky Mountains National Park, USA. Pages 295–322 *in* Kumar, Kohli R, Jose S, Pal, Singh H, Rani, Batish D, eds. Invasive Plants and Forest Ecosystems. New York: CRC

Keeley JE (2006) Fire management impacts on invasive plants in the western United States. Conserv Biol 20:375–384

Kettenring KM, Adams CR (2011) Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. J Appl Ecol 48:970–979

Lodge DM, Williams S, MacIsaac HJ, Hayes KR, Leung B, Reichard S, Mack RN, Moyle PB, Smith M, Andow DA, Carlton JT, McMichael A (2006) Biological invasions: recommendations for US policy and management. Ecol Appl 16:2035–2054

Love JP, Anderson JT (2009) Seasonal effects of four control methods on the invasive Morrow's honeysuckle (*Lonicera morrowii*) and initial responses of understory plants in a southwestern Pennsylvania old field. Restor Ecol 17:549–559

Maxwell BD, Lehnhoff E, Rew LJ (2009) The rationale for monitoring invasive plant populations as a crucial step for management. Invasive Plant Sci Manag 2:1–9

Møller AP, Jennions MD (2001) Testing and adjusting for publication bias. Trends Ecol Evol 16:580–586

Morales CL, Traveset A (2009) A meta-analysis of impacts of alien vs. native plants on pollinator visitation and reproductive success of co-flowering native plants. Ecol Lett 12:716–728

Moyes AB, Witter MS, Gamon JA (2005) Restoration of native perennials in a California annual grassland after prescribed spring burning and solarization. Restor Ecol 13:659–666

National Park Service (2006) Management Policies 2006. U.S. Department of the Interior, National Park Service. Washington, DC: US Government Printing Office

Natural Resources Conservation Service (2013) The PLANTS database. http://plants.usda.gov. Accessed April 10, 2013

Organic Act (1916) 39 Stat. F35. http://www.law.cornell.edu/uscode/text/16/1. Accessed December 17, 2013

Pernas AJ, Snyder WA (1999) Status of melaleuca control at Big Cypress National Preserve. Pages 133–137 *in* Jones DT, Gamble BW, eds. Florida's Garden of Good and Evil: Proceedings of a Joint Conference of the Florida Exotic Pest Plant Council and the Florida Native Plant Society. West Palm Beach, FL: South Florida Water Management District

Pimentel D, Zuniga R, Morrison D (2005) Update on the environmental and economic costs associated with alien–invasive species in the United States. Ecol Econ 52:273–288

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. Glob Change Biol 18:1725–1737

Ransom CV, Christensen SD, Edvarchuk KA, Naumann T (2012) A reinventory of invasive weed species in Dinosaur National Monument to determine management effectiveness. Invasive Plant Sci Manag 5: 300–309

Reid AM, Morin L, Downey PO, French K, Virtue JG (2009) Does invasive plant management aid the restoration of natural ecosystems? Biol Conserv 142:2342–2349

Rejmánek M, Richardson DM, Higgins SL, Pitcairn MJ, Grotkopp E (2005) Ecology of invasive plants: state of the art. Pages 104–161 *in* Mooney HA, Mack RN, McNeely JA, Neville LE, Schei PJ, Waage JK, eds. Invasive Alien Species: A New Synthesis. Washington, DC: Island

Rinella MJ, Maxwell BD, Fay PK, Weaver T, Sheley RL (2009) Control effort exacerbates invasive-species problem. Ecol Appl 19:155–162

Santos GL, Kageler D, Gardner DE, Cuddihy LW, Stone CP (1992) Herbicidal control of selected alien plant species in Hawaii Volcanoes National Park. Pages 341–375 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Shafer CL (2012) Chronology of awareness about US national park external threats. Environ Manag 50:1098–1110

Sheley RL, James JJ, Rinella MJ, Blumenthal D, DiTomaso JM (2011) Invasive plant management on anticipated conservation benefits: a scientific assessment. Pages 291–336 *in* Briske DD, ed. Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps. Lawrence, KS: Allen

Simmons MT, Windhager S, Power P, Lott J, Lyons RK, Schwope C (2007) Selective and non-selective control of invasive plants: the short-term effects of growing-season prescribed fire, herbicide, and mowing in two Texas prairies. Restor Ecol 15:662–669

Snyder JR (1999) Seasonal variation in resprouting ability of native and exotic hardwoods in South Florida. Pages 257–269 *in* Jones DT, Gamble BW, eds. Florida's Garden of Good and Evil: Proceedings of a Joint Conference of the Florida Exotic Pest Plant Council and the Florida Native Plant Society. West Palm Beach, FL: South Florida Water Management District

Steers RJ, Allen EB (2010) Post-fire control of invasive plants promotes native recovery in a burned desert shrubland. Restor Ecol 18(Suppl 2):334–343

Tunison JT (1992) Alien plant control strategies in Hawaii Volcanoes National Park. Pages 485–505 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Tunison JT, Zimmer NG (1992) Success in controlling localized alien plants in Hawaii Volcanoes National Park. Pages 506–524 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Tyser RW, Asebrook JM, Potter RW, Kurth LL (1998) Roadside revegetation in Glacier National Park, U.S.A.: effects of herbicide and seeding treatments. Restor Ecol 6:197–206

Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, Pergl J, Schaffner U, Sun Y, Pyšek P (2011) Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems. Ecol Lett 14:702–708

Whipple JL (2001) Annotated checklist of exotic vascular plants in Yellowstone National Park. West N Am Nat 61:336–346

Wolf JJ (2008) Fighting fire with fire: restoring montane grasslands and controlling *Melilotus* in Rocky Mountain National Park. Ecol Restor 26:219–228

Received August 1, 2013, and approved November 18, 2013.

Appendix 1. Summary of studies assessing effects of exotic plant treatments on National Park Service lands in the United States. Studies are arranged from the Pacific Islands to the eastern and western lower 48 states.

Reference	Park[a]	State/ territory	Vegetation	Focal exotic species
Santos et al. (1992)	Hawaii Volcanoes NP	Hawaii	Various	Various
Tunison (1992a)	Hawaii Volcanoes NP	Hawaii	Prairie	*Pennisetum setaceum*
Tunison (1992b)	Hawaii Volcanoes NP	Hawaii	Various	Various
Tunison and Zimmer (1992)	Hawaii Volcanoes NP	Hawaii	Various	Various
Hughes and Vitousek (1993)	Hawaii Volcanoes NP	Hawaii	Forest	*Schizachyrium condensatum*, others
D'Antonio et al. (1998)	Hawaii Volcanoes NP	Hawaii	Forest	*Schizachyrium condensatum*
Loh and Daehler (2007, 2008)	Hawaii Volcanoes NP	Hawaii	Forest	*Morella faya*
Daehler and Goergen (2005)	Puukohola Heiau National Historic Site	Hawaii	Prairie	*Pennisetum ciliare*
Hughes et al. (2012)	NP of American Samoa	American Samoa	Forest	*Falcataria moluccana*
Burkhead (1991)	Big Cypress National Preserve	Florida	Prairie/ forest	*Melaleuca quinquenervia*
Molnar et al. (1991)	Everglades NP	Florida	Wetland	*Melaleuca quinquenervia*
Pernas and Snyder (1999)	Big Cypress National Preserve	Florida	Wetland	*Melaleuca quinquenervia*
Snyder (1999)	Big Cypress National Preserve, Everglades NP	Florida	Wetland	*Melaleuca quinquenervia*, *Schinus terebinthifolius*
Myers et al. (2001)	Big Cypress National Preserve	Florida	Wetland	*Melaleuca quinquenervia*
Doren and Whiteaker (1990), Doren et al. (1991)	Everglades NP	Florida	Wetland	*Schinus terebinthifolius*
Dalrymple et al. (2003)	Everglades NP	Florida	Wetland	*Schinus terebinthifolius*
Price and Weltzin (2003)	Great Smoky Mountains NP	Tennessee	Forest	Various
Faulkner et al. (1989)	Chickamauga and Chattanooga National Military Park	Georgia	Forest	*Lonicera japonica*, *Ligustrum sinense*
Greller et al. (2000)	Gateway National Recreation Area	New York	Wetland	*Polygonum cuspidatum*
Burch and Zedaker (2003)	Shenandoah NP	Virginia	Forest	*Ailanthus altissima*
Love and Anderson (2009)	Fort Necessity National Battlefield	Pennsylvania	Forest	*Lonicera morrowii*
Wilcox et al. (1988)	Indiana Dunes National Lakeshore	Indiana	Wetland	*Lythrum salicaria*
Choi and Pavlovic (1994, 1998)	Indiana Dunes National Lakeshore	Indiana	Forest	Perennial grasses
Pavlovic et al. (2009)	Indiana Dunes National Lakeshore	Indiana	Forest	*Hesperis matronalis*
Baskett et al. (2011), Emery et al. (2013)	Sleeping Bear Dunes National Lakeshore	Michigan	Forest	*Gypsophila paniculata*
Larson et al. (2007)	Theodore Roosevelt NP	North Dakota	Shrubland	*Euphorbia esula*
Forde et al. (1984)	Wind Cave NP	South Dakota	Prairie	*Bromus japonicus*, *Melilotus* spp.
Simmons et al. (2007)	Lyndon B. Johnson National Historical Park	Texas	Prairie	*Bothriochloa ischaemum*
Whipple (2001)	Yellowstone NP	Montana, Wyoming	Various	Various
Tyser et al. (1998)	Glacier NP	Montana	Prairie	*Centaurea stoebe*, *Phleum pratense*, others
Wolf (2008)	Rocky Mountain NP	Colorado	Prairie	*Melilotus officinalis*, *Melilotus alba*
Floyd et al. (2006)	Mesa Verde NP	Colorado	Woodland	*Bromus tectorum, Carduus nutans,* others
Ransom et al. (2012)	Dinosaur National Monument	Utah	Desert	*Acroptilon repens*, others
Fuhrmann et al. (2009)	Zion NP	Utah	Woodland	*Bromus tectorum*, *Bromus madritensis*
Brisbin et al. (2013)	Zion NP	Utah	Desert	*Bromus tectorum*, *B. madritensis*

https://doi.org/10.1614/IPSM-D-13-00058.1 Published online by Cambridge University Press

Appendix 1. Extended.

Treatments	Comparison[b]	Pretreatment[c]	Years posttreatment[d]	Focal exotic[e]	Native species	Other exotic
H, C	Yes	Yes	1	↓	0	—
P	No	No	6	↓	—	—
Various	No	No	Various	↓	—	—
P, H	No	No	Various	↓	—	—
Cleared	No	No	1	—	↑	—
P	No	No	3	—	↑	—
C + H, G + H	Yes	Yes	3	↓	↑	↑
B, P, H	Yes	Yes	4	↓	↑	0
G	No	No	3, 6	↓	↑	—
C + H	Yes	No	1	↓	—	—
C + H	No	No	3	↓	—	—
C, H, clear	Yes	Yes	5	↓	—	—
C	No, T	Yes	2	↓	—	—
B	No	No	2	↓	—	—
B	No	No	6	0	—	↑
Soil removal	Yes	No	8	↓	—	—
B + H	No	Yes	4	0	0	—
B, H	Yes, T	Yes	1	↓	—	—
M	No	Yes	5	0	—	—
C, H	Yes	No	1	↓	↑	0
C, H, clear	Yes, T	Yes	1	↓	↑	↑
C, fertilize natives	No	Yes	< 1	↓	↑	—
B, H, sod removal	Yes	Yes	3	↓	↑	0
P	No	Yes	3	↓	0	↑
P, H	Yes	Yes	3	↓	↑	0
H	Yes	No	3	0	—	—
B	No	Yes	2	0	0	—
B, H, M	Yes, T	Yes	1	↓	↓	—
P, H	No	No	Various	↓	—	—
H, PN	No	No	3	0	0	—
B	No	Yes	1	↓	0	0
PN, H, clear	No	No	6	↓	↑	↓
H, C, grazing, M	No	Yes	1–5	↓	—	—
H, PN	Yes	No	1	↓	↓	—
H	No	No	3	↓	0	—

https://doi.org/10.1614/IPSM-D-13-00058.1 Published online by Cambridge University Press

Appendix 1. Continued.

Reference	Park[a]	State/ territory	Vegetation	Focal exotic species
Belote et al. (2010)	Grand Canyon NP	Arizona	Desert	*Tamarix* spp.
Reynolds and Cooper (2011)	Canyon de Chelly National Monument	Arizona	Desert	*Tamarix* spp., *Elaeagnus angustifolia*
Woods et al. (2012)	Saguaro NP	Arizona	Desert	*Pennisetum ciliare*
Abella et al. (2013a)	Saguaro NP	Arizona	Desert	*Pennisetum ciliare*
Rutman and Dickson (2002)	Organ Pipe Cactus National Monument	Arizona	Desert	*Pennisetum ciliare*
Harms and Hiebert (2006)	Lake Mead National Recreation Area, Arches NP, Canyonlands NP, Petrified Forest NP	Nevada, Arizona, Utah	Desert	*Tamarix* spp.
Bay and Sher (2008)	Lake Mead National Recreation Area	Nevada, Arizona	Desert	*Tamarix* spp.
Abella et al. (2009)	Lake Mead National Recreation Area	Nevada, Arizona	Desert	*Nicotiana glauca*, *Peganum harmala*
Abella et al. (2013b)	Lake Mead National Recreation Area	Nevada, Arizona	Desert	*Brassica tournefortii*
Randall (1991)	Yosemite NP	California	Forest	*Cirsium vulgare*
Ordóñez and Schweizer (2003)	Yosemite NP	California	Forest	*Rubus discolor*
Pollak (2008)	Golden Gate National Recreation Area	California	Forest	*Muehlenbeckia complexa*
Alexander and D'Antonio (2003a)	Golden Gate National Recreation Area, Point Reyes National Seashore	California	Prairie	*Genista monspessulana*, *Cytisus scoparius*
Alexander and D'Antonio (2003b)	Point Reyes National Seashore	California	Prairie	*Genista monspessulana*
Halvorson (1992)	Channel Islands NP	California	Prairie	*Erechtites glomerata*
Dash and Gliessman (1994)	Channel Islands NP	California	Prairie	*Foeniculum vulgare*
Brenton and Klinger (2002)	Channel Islands NP	California	Prairie	*Foeniculum vulgare*
Erksine Ogden and Rejmánek (2005)	Channel Islands NP	California	Prairie	*Foeniculum vulgare*
Brigham (2004)	Santa Monica Mountains National Recreation Area	California	Shrubland	*Brassica nigra*, *Foeniculum vulgare*, others
Moyes et al. (2005)	Santa Monica Mountains National Recreation Area	California	Prairie	*Bromus diandrus*, *Brassica nigra*, others
Mitchell and Bakker (2011)	Ebey's Landing National Historical Reserve	Washington	Prairie	Various

[a] Abbreviations: NP, national park; B, burning; C, cutting; G, girdling; H, herbicide; M, mowing; P, pulling; PN, planting natives; T, temporal comparisons of treatments.

[b] Yes or no for whether a study compared different treatment types.

[c] Yes or no for whether pretreatment data were collected.

[d] The longest duration after treatments were implemented that assessment was performed.

[e] Response of focal exotic species, native species, and other exotic species are indicated as increasing (↑), neutral (0), or decreasing (↓). Dashes indicate not measured.

Appendix 1. Extended Continued.

Treatments	Comparison[b]	Pretreatment[c]	Years posttreatment[d]	Focal exotic[e]	Native species	Other exotic
C + H	No	Yes	1–3	↓	0	0
C + H, clear	Yes	Yes	2	↓	↑	↓
P, H, PN	No	Yes	2	0	0	—
P, H	Yes	No	4	↓	0	—
P	No	Yes	1	↓	—	—
B, C + H	Yes	No	1–6	↓	↑	0
B, H, clear	No	No	2–12	—	↑	—
P, H	No	Yes	3	↓	—	—
P, H	Yes, T	No	< 1	↓	—	—
C and remove, leave	Yes	No	1	↓	—	—
P, digging, tilling	No	Yes	1	↓	—	—
C, H, scraping, fabric	Yes	Yes	1	↓	—	—
P, C, B	Yes	No	1–3	↓	↑	—
B	Yes	No	1–2	↓	0	↑
P	No	Yes	3	↓	—	—
C, H, uproot	Yes	No	3	↓	↑	—
C, H	No	Yes	3	↓	↑	—
B + H	No	Yes	4	↓	0	↑
Mulch, PN	Yes	No	1	↓	—	—
B, solarization	Yes	No	<1	↓	—	↑
Carbon addition	Yes, T	No	1	↓	—	—

Appendix 1 Literature Cited

Abella SR, Chiquoine LP, Backer DM (2013a) Soil, vegetation, and seed bank of a Sonoran Desert ecosystem along an exotic plant (*Pennisetum ciliare*) treatment gradient. Environ Manag 52:946–957

Abella SR, Spencer JE, Hoines J, Nazarchyk C (2009) Assessing an exotic plant surveying program in the Mojave Desert, Clark County, Nevada, USA. Environ Monit Assess 151:221–230

Abella SR, Suazo AA, Norman CM, Newton AC (2013b) Treatment alternatives and timing affect seeds of African mustard (*Brassica tournefortii*), an invasive forb in American Southwest arid land. Invasive Plant Sci Manag. 6:559–567

Alexander JM, D'Antonio CM (2003a) Control methods for the removal of French and Scotch broom tested in coastal California. Ecol Restor 21:191–198

Alexander JM, D'Antonio CM (2003b) Seed bank dynamics of French broom in coastal California grasslands: effects of stand age and prescribed burning on control and restoration. Restor Ecol 11:185–197

Baskett CA, Emery SM, Rudgers JA (2011) Pollinator visits to threatened species are restored following invasive plant removal. Int J Plant Sci 172:411–422

Bay RF, Sher AA (2008) Success of active revegetation after *Tamarix* removal in riparian ecosystems of the southwestern United states: a quantitative assessment of past restoration projects. Restor Ecol 16: 113–128

Belote RT, Makarick LJ, Kearsley MJC, Lauver CL (2010) Tamarisk removal in Grand Canyon National Park: changing the native–non-native relationship as a restoration goal. Ecol Restor 28:449–459

Brenton RK, Klinger RC (2002) Factors influencing the control of fennel (*Foeniculum vulgare* Miller) using triclopyr on Santa Cruz Island, California, USA. Nat Areas J 22:135–147

Brigham C (2004) Clumped planting arrangement reduces weed establishment in coastal sage scrub restoration experiment (California). Ecol Restor 22:299

Brisbin H, Thode A, Brooks M, Weber K (2013) Soil seedbank responses to postfire herbicide and native seeding treatments designed to control *Bromus tectorum* in a pinyon–juniper woodland at Zion National Park, USA. Invasive Plant Sci Manag 6:118–129

Burch PL, Zedaker SM (2003) Removing the invasive tree *Ailanthus altissima* and restoring natural cover. J Arboric 29:18–24

Burkhead RR (1991) Melaleuca control in Big Cypress National Preserve. Pages 63–72 *in* Center TD, Doren RF, Hofstetter RL, Myers RL, Whiteaker LD, eds. Proceedings of the Symposium on Exotic Pest Plants. Denver, CO: National Park Service Technical report NPS/NREVER/NRTR-91/06. 388 p

Choi YD, Pavlovic NB (1994) Comparison of fire, herbicide, and sod removal to control exotic vegetation. Nat Areas J 14:217–218

Choi YD, Pavlovic NB (1998) Experimental restoration of native vegetation in Indiana Dunes National Lakeshore. Restor Ecol 6:118–129

Daehler CC, Goergen EM (2005) Experimental restoration of an indigenous Hawaiian grassland after invasion by buffel grass (*Cenchrus ciliaris*). Restor Ecol 13:380–389

Dalrymple GH, Doren RF, O'Hare NK, Norland MR, Armentano TV (2003) Plant colonization after complete and partial removal of disturbed soils for wetland restoration of former agricultural fields in Everglades National Park. Wetlands 23:1015–1029

D'Antonio CM, Hughes RF, Mack M, Hitchcock D, Vitousek PM (1998) The response of native species to removal of invasive exotic grasses in a seasonally dry Hawaiian woodland. J Veg Sci 9:699–712

Dash BA, Gliessman SR (1994) Nonnative species eradication and native species enhancement: fennel on Santa Cruz Island. Pages 505–512 *in* Halvorson W, Maender G, eds. Fourth California Islands Symposium: Update on the Status of Resources. Santa Barbara, CA: Santa Barbara Museum of Natural History

Doren RF, Whiteaker LD (1990) Effects of fire on different size individuals of *Schinus terebinthifolius*. Nat Areas J 10:106–113

Doren RF, Whiteaker LD, Larosa AM (1991) Evaluation of fire as a management tool for controlling *Schinus terebinthifolius* as secondary successional growth on abandoned agricultural land. Environ Manag 15:121–129

Emery SM, Drohan PJ, Legge JT, Kleitch M, Howard S (2013) Aboveground and belowground impacts following removal of the invasive species baby's breath (*Gypsophila paniculata*) on Lake Michigan sand dunes. Restor Ecol 21:506–514

Erksine Ogden JA, Rejmánek M (2005) Recovery of native plant communities after the control of a dominant invasive species, *Foeniculum vulgare*: implications for management. Biol Conserv 125:427–439

Faulkner JL, Clebsch EEC, Sanders WL (1989) Use of prescribed burning for managing natural historic resources in Chickamauga and Chattanooga National Military Park, USA. Environ Manag 13:603–612

Floyd ML, Hanna D, Romme WH, Crews TE (2006) Predicting and mitigating weed invasions to restore natural post-fire succession in Mesa Verde National Park, Colorado, USA. Int J Wildland Fire 15:247–259

Forde JD, Sloan NF, Shown DA (1984) Grassland habitat management using prescribed burning in Wind Cave National Park, South Dakota. Prairie Nat 16:97–110

Fuhrmann K, Weber K, Decker C (2009) Restoring burned areas at Zion National Park (Utah). Ecol Restor 27:132–134

Greller AM, Durando C, Marcus LF, Wijesundara DSA, Byer MD, Cook R, Tanacredi JT (2000) Phytosociological analysis of restored and managed grassland habitat within an urban national park. Urban Ecosyst 4:293–319

Halvorson WL (1992) Alien plants at Channel Islands National Park. Pages 64–96 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Harms RS, Hiebert RD (2006) Vegetation response following invasive tamarisk (*Tamarix* spp.) removal and implications for riparian restoration. Restor Ecol 14:461–472

Hughes F, Vitousek PM (1993) Barriers to shrub reestablishment following fire in the seasonal submontane zone of Hawai'i. Oecologia 93:557–563

Hughes RF, Uowolo AL, Togia TP (2012) Recovery of native forest after removal of an invasive tree, *Falcataria moluccana*, in American Samoa. Biol Invasions 14:1393–1413

Larson DL, Grace JB, Rabie PA, Andersen P (2007) Short-term disruption of a leafy spurge (*Euphorbia esula*) biocontrol program following herbicide application. Biol Control 40:1–8

Loh RK, Daehler CC (2007) Influence of invasive tree kill rates on native and invasive plant establishment in a Hawaiian forest. Restor Ecol 15:199–211

Loh RK, Daehler CC (2008) Influence of woody invader control methods and seed availability on native and invasive species establishment in a Hawaiian forest. Biol Invasions 10:805–819

Love JP, Anderson JT (2009) Seasonal effects of four control methods on the invasive Morrow's honeysuckle (*Lonicera morrowii*) and initial responses of understory plants in a southwestern Pennsylvania old field. Restor Ecol 17:549–559

Mitchell RM, Bakker JD (2011) Carbon addition as a technique for controlling exotic species in Pacific Northwest prairies. Northwest Sci 85:247–254

Molnar G, Hofstetter RH, Doren RF, Whiteaker LD, Brennan MT (1991) Management of *Melaleuca quinquenervia* within East Everglades wetlands. Pages 237–253 *in* Center TD, Doren RF, Hofstetter RL, Myers RL, Whiteaker LD, eds. Proceedings of the Symposium on Exotic Pest Plants. Denver, CO: National Park Service Technical report NPS/NREVER/NRTR-91/06

Moyes AB, Witter MS, Gamon JA (2005) Restoration of native perennials in a California annual grassland after prescribed spring burning and solarization. Restor Ecol 13:659–666

Myers RL, Belles HA, Snyder JR (2001) Prescribed fire in the management of *Melaleuca quinquenervia* in subtropical Florida. Pages 132–140 *in* Galley KEM, Wilson TP, eds. Proceedings of the Invasive Species Workshop: the Role of Fire in the Control and Spread of Invasive Species. Fire Conference 2000: the First National Congress on Fire Ecology, Prevention, and Management. Misc. Pub.11. Tallahassee, FL: Tall Timbers Research Station

Ordóñez L, Schweizer D (2003) Tilling shows promise for controlling Himalayan blackberry in Yosemite Valley (California). Ecol Restor 21:54–55

Pavlovic NB, Leicht-Young SA, Frohnapple KJ, Grundel R (2009) Effect of removal of *Hesperis matronalis* (Dame's rocket) on species dover of forest understory vegetation in NW Indiana. Am Midl Nat 161:165–176

Pernas AJ, Snyder WA (1999) Status of melaleuca control at Big Cypress National Preserve. Pages 133–137 *in* Jones DT, Gamble BW, eds. Florida's Garden of Good and Evil: Proceedings of a Joint Conference of the Florida Exotic Pest Plant Council and the Florida Native Plant Society. West Palm Beach, FL: South Florida Water Management District

Pollak T (2008) Control of maidenhair vine (*Muehlenbeckia complexa*) (California). Ecol Restor 26:16–18

Price CA, Weltzin JF (2003) Managing non-native plant populations through intensive community restoration in Cades Cove, Great Smoky Mountains National Park, U.S.A. Restor Ecol 11:351–358

Randall JM (1991) Population dynamics and control of bull thistle, *Cirsiuim vulgare*, in Yosemite Valley. Pages 261–281 *in* Center TD, Doren RF, Hofstetter RL, Myers RL, Whiteaker LD, eds. Proceedings of the Symposium on Exotic Pest Plants. Denver, CO: National Park Service Technical report NPS/NREVER/NRTR-91/06

Ransom CV, Christensen SD, Edvarchuk KA, Naumann T (2012) A reinventory of invasive weed species in Dinosaur National Monument to determine management effectiveness. Invasive Plant Sci Manag 5:300–309

Reynolds LV, Cooper DJ (2011) Ecosystem response to removal of exotic riparian shrubs and a transition to upland vegetation. Plant Ecol 212:1243–1261

Rutman S, Dickson L (2002) Management of buffelgrass on Organ Pipe Cactus National Monument, Arizona. Pages 311–318 *in* Tellman B, ed. Invasive Exotic Species in the Sonoran Pegion. Tucson: University of Arizona Press and Arizona-Sonora Desert Museum

Santos GL, Kageler D, Gardner DE, Cuddihy LW, Stone CP (1992) Herbicidal control of selected alien plant species in Hawaii Volcanoes National Park. Pages 341–375 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Simmons MT, Windhager S, Power P, Lott J, Lyons RK, Schwope C (2007) Selective and non-selective control of invasive plants: the short-term effects of growing-season prescribed fire, herbicide, and mowing in two Texas prairies. Restor Ecol 15:662–669

Snyder JR (1999) Seasonal variation in resprouting ability of native and exotic hardwoods in South Florida. Pages 257–269 *in* Jones DT, Gamble BW, eds. Florida's Garden of Good and Evil: Proceedings of a Joint Conference of the Florida Exotic Pest Plant Council and the Florida Native Plant Society. West Palm Beach, FL: South Florida Water Management District

Tunison JT (1992a) Fountain grass control in Hawaii Volcanoes National Park: management considerations and strategies. Pages 376–393 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Tunison JT (1992b) Alien plant control strategies in Hawaii Volcanoes National Park. Pages 485–505 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Tunison JT, Zimmer NG (1992) Success in controlling localized alien plants in Hawaii Volcanoes National Park. Pages 506–524 *in* Stone CP, Smith CW, Tunison JT, eds. Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. Honolulu: University of Hawaii Press

Tyser RW, Asebrook JM, Potter RW, Kurth LL (1998) Roadside revegetation in Glacier National Park, U.S.A.: effects of herbicide and seeding treatments. Restor Ecol 6:197–206

Whipple JL (2001) Annotated checklist of exotic vascular plants in Yellowstone National Park. West N Am Nat 61:336–346

Wilcox DA, Seeling MK, Edwards KR (1988) Ecology and management potential for purple loosestrife (*Lythrum salicaria*). Pages 120–129 *in* Thomas LK, ed. Proceedings of the Conference on Science in the National Parks. Washington, DC: National Park Service

Wolf JJ (2008) Fighting fire with fire: restoring montane grasslands and controlling *Melilotus* in Rocky Mountain National Park. Ecol Restor 26:219–228

Woods SR, Fehmi JS, Backer DM (2012) An assessment of revegetation treatments following removal of invasive *Pennisetum ciliare* (buffelgrass). J Arid Environ 87:168–175