Improving Management of Nonnative Invasive Plants in Wilderness and Other Natural Areas

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Abstract—Nonnative invasive plants invade wilderness and other natural areas throughout North America and invasive organisms as a group are now considered the second worst threat to biodiversity, behind only habitat loss and fragmentation. In the past 10-20 years there have been upsurges in interest in the ecology of plant invasions among researchers and in concern about how to prevent and control them among land managers. Much research has focused on how to identify and predict which species are most likely to be invasive and which habitats or areas are most likely to be invaded and some progress has been made. A number of studies clearly demonstrate that plant invasions can alter ecosystem processes, displace native species, promote nonnative animals, fungi or microbes and alter the genetic make up of native species populations through hybridization. Some invasions can be prevented or controlled and efforts continue to refine and improve current techniques. Improved prevention and management of invasive plants will require development and use of adaptive management strategies, tools to help managers set weed control priorities, techniques for using remote sensing technologies to map weed infestations, improved control methods and increased attention to preventing new invasions and quickly detecting and eradicating those that do occur.

Nonnative invasive plants have dramatically changed North America's ecological landscape. They are most notorious for invading island ecosystems and sites subjected to human or natural disturbances, but they also invade large mainland wildernesses and natural areas that appear to have suffered no other disturbance in recent decades. Nonnative plants were recognized as a problem and an interesting topic of study by the mid-1800s, but interest among ecologists picked up markedly following publication of Elton's (1958) book "The Ecology of Invasions by Animals and Plants." A great deal of interest and work has been directed at discovering what, if anything, makes some species more invasive than others and what, if anything, makes some habitats and systems more susceptible to invasion than others. Answers to these questions remain elusive, but there have been significant new findings in the past few years. This has rekindled hopes that we may yet gain enough understanding of these phenomena to make more reliable predictions, which could be used to help prevent new invasions.

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There has also been interest and concern about invasive weeds among managers of wilderness and other natural areas since at least the mid-1800s and both have risen sharply in the past 10-15 years. This concern has grown in part because we have learned more about the impacts invasive weeds can have. Some alter the ecosystems and communities they infest, using resources that would have been consumed by native species and altering wildlife habitats in ways that make these places unfit for native animals. Some invasive species like the tamarisks (*Tamarix* spp.), cheat grass (*Bromus tectorum*), Scotch broom (*Cytisus scoparius*) and European beachgrass (*Ammophila arenaria*) completely alter natural ecosystem functions and processes, such as fire patterns, nutrient cycling, soil stability and hydrological regimes. In so doing, they 'change the rules of the game' of survival and growth, placing many native species at a gross disadvantage. Even when they don't noticeably affect ecosystem processes, invasive plants outcompete and displace native plants, which in turn displaces native animals. Some invasive plants also hybridize with native species and with time could eliminate purely native strains. For example, in some tidal creeks around the San Francisco Bay, it is now impossible to find 'pure' native strains of California Cord grass (*Spartina foliosa*) – every plant has at least some genes from the invasive Atlantic cord grass (*S. alterniflora*) (Ayres and others in press).

Invasive species are now widely recognized as threats to native biological diversity second only to direct habitat loss and fragmentation (Pimm and Gilpin 1989; Scott and Wilcove 1998). In fact, when biological invasion is considered as a single phenomenon, it is clear that, to date, it has had greater impacts on the biota worldwide than more notorious aspects of global environmental change such as rising CO_2 concentrations, climate change and decreasing stratospheric ozone levels (Vitousek and others 1996). What's worse is that invasive organisms continue to spread on their own and do not degrade with time, unlike pollutants; once introduced, they can spread from site to site, region to region, without further human assistance.

Fortunately, many plant invasions into wildlands can be halted or slowed, and, in certain situations, even badly infested areas can be restored to relatively healthy communities dominated by native species (for example, see Barrows 1993; Pickart and Sawyer 1998; Randall and others 1997). Because control and restoration efforts can limit or reverse the severe damage caused by invasive plants, these activities are now widely regarded as necessary in many natural areas. This need has driven a great deal of research and demonstration work aimed at developing better techniques to kill or suppress unwanted weeds without harming desirable native plants and animals. One technique that has received a great deal of attention is classical biological control—the release of host-specific natural enemies (pathogens, parasites and herbivores) from the native range of the weed into the invaded environment. Although sometimes the only practical method available for controlling invasive weeds across vast areas, this technique can backfire if the biocontrol agent is less host-specific than expected and begins feeding on and reducing populations of desirable native species. Fortunately, some recent work urges greater caution in the selection of biocontrol agents and suggests concrete ways to accomplish this (Louda and others 1997; McEvoy and Coombs 1999). Unfortunately, we have far too little quantitative information about the impacts of biocontrol agents or of other weed control techniques on the native species, communities and systems we are trying to protect. This information is of utmost concern since controlling the weed(s) is only a means to our ultimate goal of protecting or restoring the natives.

The need to use limited resources efficiently to prevent and control invasive weed problems has driven land managers to set priorities and adopt adaptive management approaches for weed management.

Definitions of Terms

Nonnative plants are those species beyond their natural range or natural zone of potential dispersal, including all domesticated and feral species and all hybrids involving at least one nonnative parent species. Other terms that are often used as synonyms for nonnative include alien, exotic, introduced, adventive, nonindigenous, nonaboriginal and naturalized. With rare exceptions, conservation programs are dedicated to the preservation of native species and communities. The addition of nonnative species rarely contributes positively to this, unless they alter the environment in ways that favor native species, as some grazers and biological control agents do.

Natural ranges should not be confused with political or administrative boundaries. Bush lupine (*Lupinus arboreus*), for example, may be thought of as a California native, but its original, native range is only the central and southern coasts of the state. It is a nonnative along the north coast, where it was intentionally planted outside its natural range (Miller 1988). All hybrids between introduced or domesticated species and native species are also nonnative.

Invasive species are those that spread into areas where they are not native (Rejmánek 1995). Not all nonnative plants are invasive; in fact, only a minority of introduced species have escaped cultivation, and only a minority of those that have escaped are invasive in wildlands.

The terms **pest plant** and **weed** may be used interchangeably to refer to species, populations and individual plants that are unwanted because they interfere with management goals and objectives. Plants regarded as pests in some wildlands may not be troublesome elsewhere. For example, the Empress tree (*Paulownia tomentosa*) is a pest in deciduous forests of the eastern U.S., particularly in the southern Appalachians, but it is not known to escape from cultivation in California, although it is often used as an ornamental landscape tree there. Some species that are troublesome in agricultural or urban areas rarely, if ever, become weeds of wildlands. The term environmental weeds is used by many Australians (Groves 1991; Humphries and others 1991) to refer to wildland weeds, but few North America land managers or researchers use this term.

Research on Invasive Weed Ecology and Control: What Have We Learned and How Has It Helped Us Manage Wilderness and Other Natural Areas?

Early Recognition of the Issue in Natural Areas and Increasing Recognition of Its Importance

Invasions by nonnative species have been recognized as an important topic of study for natural history and ecology for nearly 150 years. Charles Darwin (1859) commented on the phenomenon of nonnative plants invading new areas and put forth hypotheses about what might predispose certain areas to be prone to invasion and what might predispose certain species to be invasive. Here in North America, the impacts of invasive nonnative weeds on the native biota of designated natural areas were recognized at least as early as 1865 by Frederick Law Olmsted. He filed a report on the newly set-aside Yosemite Valley, noting that unless actions were taken, its vegetation would likely be pushed out by common weeds from Europe. The report pointed out that this had already happened "in large districts of the Atlantic States." Botanists and other students of natural history noted the establishment of nonnative species across the continent in published papers. By the 1930s, natural area managers in Yosemite and scattered parks and preserves around the nation began controlling invading nonnative species that were recognized as agricultural pests (Randall 1991). Invasive species impacts were brought into the mainstream of ecology in the late 1950s with the publication of Charles Elton's book , The Ecology of Invasions by Animals and Plants (1958). Concern and interest among both land managers and researchers has grown since then, particularly since the mid-1980s.

Research on 'Invasiveness'—What Characteristics Enable Certain Species to Invade New Areas?

Many people have wondered if certain traits distinguish species that become invasive from those that don't. Despite a great deal of study, no single answer presents itself, and researchers have been surprised by the success of some species and the failure of others. It has proven even more difficult to find traits that distinguish between the subset of successful invading species that become pests from those that appear to have little impact. Work on this topic continues, in part because of the hope that answers may enable us to predict which of the many nonnative species not yet established are most likely to invade and become pests if given the chance.

Recent work points to several factors that may help predict which species are likely to be invasive. In two studies, the best predictor was whether a species was invasive somewhere else (Panetta 1993; Reichard and Hamilton 1997). For example, if a species native to Spain is invasive in Australia, it is likely to be invasive in California and South Africa as well. Rejmánek and Richardson (1996) analyzed characteristics of 20 species of pines and found that species which produce many small seeds and which begin reproducing within their first few years are most likely to be invasive. When they extended the analysis to a group of flowering trees, these same characteristics usually discriminated between invasive and noninvasive species. This study and several others also found that plants with animal-dispersed seeds, like bush honeysuckles or privets, are much more likely to be invasive in forested communities (Reichard 1997; Reichard and Hamilton 1997). It has also been suggested that species capable of reproducing both by seed and vegetative growth have a better chance to spread in a new land (Reichard 1997).

Self-compatible species, with individuals that can fertilize themselves, have been thought more likely to invade since just one plant of this type could start an invasion (Baker 1965). Many self-incompatible species are successful invaders, however, including some that are dioecious (male and female flowers on separate plants). It is also thought that plants dependent on one or a few other species for pollination, fruit dispersal or the uptake of nutrients from the soil are less likely to invade new areas unless these organisms are introduced at the same time. As a group, figs may be relatively poor invaders because, with few exceptions, each species is pollinated by a distinctive species of wasp, which is in turn dependent on that species of fig. On the other hand, the edible fig's pollinator was introduced intentionally to promote fruit production, and now the species is invasive in parts of California (Randall in press). Other plant invasions may also be promoted by introduced animals. For example, honeybees boost seed production of invaders whose flowers they favor (Barthell and others in prep). In Hawaii, feral pigs promote the spread of banana poka (*Passiflora mollissima*) and other species by feeding voraciously on their fruits and distributing them in their scat, often in areas they have disturbed by rooting in the soil for more food.

It has also been suggested that species with relatively small DNA contents in their cell nuclei are more likely to be invasive in disturbed habitats (Rejmánek 1996). Plants that germinate and grow rapidly can quickly occupy such areas and exclude other plants following a disturbance. It turns out that under given conditions, cells with low DNA contents can usually divide and multiply more quickly, and consequently these plants grow more rapidly than species with higher cellular DNA content.

A species is most likely to invade an area with a climate similar to that in its native range, but some nonnative species now thrive in novel conditions. An analysis of the distribution of nonnative herbs of the sunflower and grass families in North America indicated that species with a larger native range in Europe and Asia are more likely to become established and to have a larger range here than species with small native ranges (Rejmánek 1995). Species with large native ranges may be well adapted to a variety of climate and soil conditions and so more likely to find suitable habitat in a new area. Some of this ability to cope with different conditions can be due to genetic differences among individuals of a species or 'genetic plasticity.' Some of it may also be due to phenotypic plasticity, the ability of any given individual of some species to cope with a variety of conditions. Another factor that may contribute to whether a plant will be likely to invade a site is whether it is closely related (e.g. in the same genus) to any native species. Plants without close relatives appear more likely to become established (Rejmánek 1996).

A species may be more likely to establish if many individuals are introduced at once or if they are introduced repeatedly. It is presumed that introductions of more individuals ensure that they will be able to find one another to mate and produce offspring and that there will be more genetic variability in the population, enabling it to cope with a wider variety of conditions. If sites where the species can successfully germinate and grow are limited in number, the chance that at least one seed scattered at random will land on an appropriate site increases as the number of seeds scattered increases. Chance may be important in other ways. For example, species that happen to be introduced at the beginning of a drought may be doomed to fail, although they might easily establish following a return to normal rainfall.

There is often a time lag of many decades or more between the first introduction of a plant and its rapid spread. As far as we know, Atlantic cord grass was present in small patches in a few spots on the Pacific coast for 50 years or more before it appeared to spread. In fact, some species that rarely spread today may turn out to be troublesome 40, 50 or more years from now. This makes it all the more pressing that we find some way of determining which species are most likely to become invasive so that we can control them now, while their populations are still small and manageable.

What Makes Certain Sites More or Less Prone to Invasion?

Another question, which has long intrigued ecologists, is why some areas appear more prone to invasion than others. Again, many hypotheses have been advanced, but we have few solid answers. It is not even clear which areas have suffered the most invasions since this may differ depending on the types of organism considered and which species are regarded as firmly established as opposed to rarely escaping from gardens or persisting around old homesites. In fact, a given area may be highly susceptible to invasion by one type of organism and highly resistant to another, while the situation might be reversed in other areas.

It is recognized that areas where vegetation and soil have been disturbed by humans or their domestic animals are more susceptible to invasion. In North America, disturbed sites are often invaded by plants native to the Mediterranean region and the fertile crescent of the Old World, where they had millennia to adapt to agricultural disturbances. Changes in streamflows, the frequency of wildfires or other environmental factors caused by dam building, firefighting and other human activities may also hinder survival of native plants and promote invasion by nonnatives. Nonetheless, reserves and protected areas are not safe from nonnative species invasions, at least in part because natural disturbances ranging from gopher mounds to hurricane damage can and do strike even the most pristine sites.

It is also safe to say that remote islands in temperate and tropical areas appear to be highly susceptible to invasions by nonnative plants and animals. For, example, nearly half (49%) of the flowering plant species found in the wild in Hawaii are nonnative (Wagner and others 1990). Most remote islands had no large native herbivores, so pigs, cattle, sheep and other grazers introduced by humans found the native plants completely unprotected by spines or chemical deterrents. Introduced grazers often denuded large areas of native vegetation, leaving them open for colonization by introduced species adapted to grazing. Islands, peninsulas such as southern Florida and other areas with low numbers of native species or without any representatives of distinctive groups appear to be more prone to invasions. For example, there are no rapidly growing woody vines native to the Hawaiian Islands, where several introduced species have become pests. Some researchers theorize that where such gaps exist, certain resources are used inefficiently if at all, resulting in 'open niches.' Nonnative species that are preadapted to exploit these resources are thus highly likely to invade such areas. Other researchers reject the concept of 'empty niches,' saying they are impossible to identify in advance and that when new species move in, they do not slip into unoccupied slots but instead use resources that would have been used by the organisms present initially, and rearrange the community.

It has also been hypothesized that areas with low numbers of native species—whether on islands or continents—are more susceptible to nonnative species invasions than species-rich areas (Elton 1958; MacArthur and Wilson 1967; McNaughton 1983). Recent experimental work in a tallgrass prairie site by Tilman (1997) supported this hypothesis, showing that small plots ($1m^2$) with relatively few native species were more prone to invasion than plots with greater native species richness. Observations by Stohlgren and others (1998; 1999) in mixed-grass prairie and in Rocky Mountain meadow and parkland sites indicated that relationships between native species abundance and invasibilty are scale dependant. Most alarmingly, they found that at landscape and biome scales, areas with higher native species richness and cover support higher numbers of exotic species too. They also found evidence that relatively resource-rich areas, and in particular riparian areas, support greater numbers of invading species and hence appear to be more prone to invasion.

History too, likely plays a large role in determining the susceptibility of a site to invasion too. Sites like busy seaports, railroad terminals or military supply depots are exposed to more introductions. People from some cultures are more likely to intentionally introduce plants from their homelands when they migrate to new regions. In fact, colonization of much of the Americas, Australia and other areas of the world by western European peoples and the plants and animals from their homelands may go hand in hand, the successes of one species further promoting the successes of the others. European colonists were followed, sometimes even preceded, by animals and plants they were familiar with and knew how to exploit, and the plants and animals benefited in turn when the people cleared native vegetation and plowed the soil.

Impacts—A Few Excellent Studies on Ecosystem and Community Impacts

Nonnative plant invasions can have a variety of effects on wildlands, including alteration of ecosystem processes, displacement of native species, support of nonnative animals, fungi or microbes, and hybridization with native species and subsequent alteration of gene pools. Some invaders move into wilderness and other areas of national parks, preserves and natural areas, where they reduce or eliminate the species and communities these sites were set aside to protect. Rare species appear to be particularly vulnerable to the changes wrought by nonnative invaders. For example, the California Natural Heritage Database (1996) indicates 181 of the state's rare plant species are experiencing threats from invasive weeds. Habitats for rare animals such as the San Clemente Sage Sparrow and the Palos Verde Blue butterfly are also being invaded and displaced by weedy species. Hobbs and Mooney (1998) point out that invasive species have already brought about local extinctions and drastic population declines for many once-common species that are likely to lead to the final endpoint of species extinction.

Although we have great volumes of anecdotal information about impacts of invasive weeds, we have too little quantitative information about these impacts and even less that has been experimentally demonstrated. Symptomatic of this were arguments by Anderson (1995) and Hager and McCoy (1998) that the negative impacts of purple loosestrife (*Lythrum salicaria*) have not been conclusively demonstrated, and thus the efforts and resources devoted to control this species may have been misplaced.

We do, however, know a great deal about the impacts of certain invasive weeds and about the variety of impacts invasive weeds can have.

Ecosystem Effects

The invasive species that cause the greatest damage are those that alter ecosystem processes such as nutrient cycling, the intensity and frequency of fire, hydrological cycles, sediment deposition and erosion (D'Antonio and Vitousek 1992; Vitousek 1986; Vitousek and Walker 1989; Vitousek and others 1987; Whisenant 1990). Cheat grass (*Bromus tectorum* L.) is a well-studied example of an invader that has altered ecosystem processes. This annual grass has invaded millions of acres of rangeland in the Great Basin, leading to widespread increases in frequency of fires from once every 60 to 110 years to once every 3 to 5 years (Billings 1990; Whisenant 1990). Native shrubs do not recover well from the more frequent fires and have been eliminated or reduced to minor components in many of these areas (Mack 1981).

Some invaders alter soil chemistry, making it difficult for native species to survive and reproduce. For example, iceplant (*Mesembryanthemum crystallinum*) accumulates large quantities of salt, which it releases after it dies. The increased salinity prevents native vegetation from reestablishing (Kloot 1983; Vivrette and Muller 1977). Scotch broom (*Cytisus scoparius*) and gorse (*Ulex europaea*) can increase the availability of nitrogen in soil. Although this increases soil fertility and overall plant growth, it probably gives a competitive advantage to nonnative species that thrive in nitrogen rich soil. Researchers have found that the nitrogen-fixing firetree (*Myrica faya*) increases soil fertility and consequently alters succession in Hawaii, (Vitousek and Walker 1989).

Wetland and riparian area invaders alter hydrology and sedimentation rates. Tamarisks (*Tamarix chinensis*; *T. ramosissima*; *T. pentandra, T. parviflora*) invade wetland and riparian areas in the southern and central California and throughout the American Southwest and are believed responsible for lowering water tables at some sites (Horton 1977). This may reduce or eliminate surface water habitats that native plants and animals need to survive (Brotherson and Field 1987; Neill 1983). For example, tamarisk invaded Eagle Borax Spring in Death Valley in the 1930s or 1940s. By the late 1960s, this large marsh had dried up, and had no visible surface water. When managers removed tamarisk from the site, surface water reappeared, and the spring and its associated plants and animals recovered (Neill 1983). Tamarisk infestations also can trap more sediments than stands of native vegetation and thus alter the shape, carrying capacity and flooding cycle of rivers, streams and washes (Blackburn and others 1982). Interestingly, the only species of *Tamarix* that is established in the southwestern U.S., but not generally regarded as invasive (athel; *T. aphylla*), is regarded as a major riparian area invader in arid central Australia (Griffin and others 1989).

Other wetland and riparian invaders and a variety of beach and dune invaders dramatically alter rates of sedimentation and erosion. One example is saltmarsh cordgrass (*Spartina alterniflora*), which is native to the U.S. Atlantic and Gulf coasts but was introduced to the Pacific coast where it invades intertidal habitats. Sedimentation rates may increase dramatically in infested areas, while nearby mudflats deprived of sediment erode and become open water areas (Sayce 1990). The net result is a sharp reduction in the area of the open intertidal areas where many migrant and resident waterfowl feed.

Coastal dunes along the Pacific coast from central California to British Columbia have been invaded and altered by European beachgrass (*Ammophila arenaria*). Dunes in infested areas are generally steeper and oriented roughly parallel to the coast rather than nearly perpendicular to it, as they are in areas dominated by *Leymus mollis, L. pacificus*, and other natives (Barbour and Johnson 1988). These weeds eliminate habitats for rare native species, such as Antioch Dunes evening-primrose (*Oenothera deltoides* ssp. howellii) and Menzies' wallflower (*Erysimum menziesii* ssp. menziesii). Species richness on foredunes dominated by European beachgrass may be just half of that on adjacent dunes dominated by *Leymus* species (Barbour and others 1976). These changes in the shape and orientation of the dunes also alter the hydrology and microclimate of the swales and other adjacent habitats, affecting species in these areas.

Some upland habitat invaders also alter erosion rates. For example, runoff and sediment yield under simulated rainfall were 56% and 192% higher on plots in western Montana dominated by spotted knapweed (*Centuarea maculosa*) than on plots dominated by native bunchgrasses (Lacey and others 1989). This species is now established in northern California and the southern Peninsular range and was recently found on an inholding within Yosemite National Park (Hrusa 1998, personal communication).

Habitat Dominance and Displacement of Native Species

Invaders that move into and dominate habitats without obviously altering ecosystem properties can nevertheless cause grave damage. They may outcompete native species, suppress native species recruitment and thus alter community structure, degrade or eliminate habitat for native animals or provide food and cover for undesirable nonnative animals. Edible fig invades riparian forests in California's Central Valley and surrounding foothills and can become a canopy dominant. Invasive vines are troublesome in forested areas across the continent. In California, for example, Cape ivy (*Delairea odorata*.) infests riparian forests along the coast from San Diego north to the Oregon border (Elliott 1994).

Nonnative subcanopy trees and shrubs invade forest understories, particularly in the Sierra Nevada and California's coast ranges. Scotch broom (*Cytisus scoparius*), French broom (*Genista monspessulana*) and Gorse (*Ulex europaea*) are especially troublesome invaders of forests and adjacent openings and coastal grasslands (Bossard 1991; Mountjoy 1979). Herbaceous species can colonize and dominate grasslands or the ground layer in forests. Eupatory (*Ageratina adenophora*) invades and dominates riparian forests along California's southern and central coast. Impacts of these ground layer invaders have not been well studied, but it is suspected that they displace native herbs and perhaps prevent recruitment of trees.

Annual grasses and forbs native to the Mediterranean region have replaced most of California's native grasslands. Invasion by these species was so rapid and complete that we do not know what the dominant native species were on the vast areas of bunchgrass lands in the Central Valley and other valleys and foothills around the state. The invasion process continues today, as medusa head (*Taeniatherum caput-medusae*) and yellow star thistle (*Centaurea solstitialis*) spread to sites already dominated by other nonnatives. Yellow starthistle is an annual that produces large numbers of seeds and grows rapidly as a seedling (Prather and Callihan 1991). It is favored by soil disturbance but invades areas that show no sign of being disturbed by humans or livestock for years and has colonized several relatively pristine preserves in California, Oregon and Idaho (Randall 1996).

Invasive, nonnative weeds can also prevent reestablishment of native species following natural or human-caused disturbance, altering natural succession. Ryegrass (*Lolium multiflorum*), used to seed burned areas in southern California, interferes with herb establishment (Keeley and others 1981) and, at least in the short term, with chaparral recovery (Gautier 1982; Schultz and others 1955; Zedler and others 1983).

Hybridization With Native Species

Some nonnatives plants hybridize with natives and could, in time, effectively eliminate native genotypes. The nonnative *Spartina alterniflora* hybridizes with the native

S. foliosa where they occur together. Recent studies found few or no individual plants without nonnative genes in some *Spartina* populations in some salt marshes around the San Francisco Bay (Ayres and others in press).

Promotion of Nonnative Animals

Many nonnative plants facilitate invasions by nonnative animals and vice versa. *Myrica faya* invasions of volcanic soils in Hawaii promote populations of nonnative earthworms, which increase rates of nitrogen burial and accentuate the impacts these nitrogen-fixing trees have on soil nutrient cycles (Aplet 1990). *Myrica faya* is in turn aided by the nonnative bird Japanese white-eye (*Zosterops japonica* Temminck), perhaps the most active of the many native and nonnative species that consume its fruits and disperse its seeds to intact forest (Vitousek and Walker 1989).

Control and Restoration Methods Continue to Develop

The past 10-20 years have seen a surge in efforts to develop better methods to control invasive weeds and restore native vegetation in natural areas. A great deal of work of this sort has been reported in journals like the *Natural Areas Journal*, *Restoration & Management Notes*, and *Restoration Ecology*. Some has even been published in journals traditionally focused more on agricultural lands and rangelands such as *Weed Science*, *Weed Technology*, and *Rangelands*. Unfortunately, even more probably remains in unpublished reports, which are unlikely to be read by those who could profit most from them, or worse, was never written up in any fashion.

A variety of weed control methods is available: manual, mechanical, encouraging competition from native plants, grazing, biocontrol, herbicides, prescribed fire, flooding and other, more novel, techniques. Each method has pluses and minuses, and research and field experience have both shown it is often best to use a combination of methods. Much study has been devoted to the use of non-chemical methods of weed control due to fears that herbicides will kill desirable species or otherwise pollute and damage the environment. Unfortunately, most manual and mechanical methods, such as hand pulling, the use of mulches and plastic sheeting are often too costly, in terms of both labor and money, to be used against large infestations. However, Pickart and Sawyer (1998) reported that a 4 ha infestation of European beachgrass (*Ammophila arenaria*) on the Lanphere Dunes area of Humboldt Bay National Wildlife Refuge was cleared using hand-labor to repeatedly pull up this deep-rooted grass. This successful effort cost $86,700/ ha in 1997 dollars, and the authors indicate that studies to develop techniques that will reduce these costs continue.

Biological control can be an extremely selective control tool, and more and more biocontrol projects targeting invasive weeds of natural areas have begun in recent years. Within the past 10 years, new biological control agents have been released against several natural area weeds, including purple loosestrife (*Lythrum salicaria*), melaleuca (*Melaleuca quinquenervia*), yellow starthistle (*Centaurea solstitialis*) and leafy spurge (*Euphorbia esula*), and one insect was released against weedy tamarisks (*Tamarix* spp.) in 1999. Research and exploration for biocontrol agents has begun for several other natural area weeds, including garlic mustard (*Alliaria petiolata*), Cape ivy (*Delaria odorata*) and the native species Phragmites (*Phragmites australis*).

Unfortunately, there is some risk that the agents might attack desirable species. Concern about the specificity of control, or lack thereof, of biocontrol agents has prevented natural area managers from embracing their use more wholeheartedly. Howarth (1991) notes that no plant species are believed to have been driven to extinction by biological control agents and suggests this may be due to the greater care and stricter guidelines for introductions of herbivores than for insect predators and pathogens. Indeed, until two years ago it was frequently stated that "classical" biological control of weeds had a proven safety record and that none of the approximately 300 insects introduced to control weeds had ever become a pest itself (DeLoach 1991; Groves 1989; LaRoche 1994). Then, Louda and others (1997) reported that the biocontrol agent *Rhinocyllus conicus* had been found attacking several native thistles, including the Platte thistle (*Cirsium canescens*) in such numbers that it was clearly capable of reducing populations of these desirable, nontarget natives.

Herbicides can be effective against many of the weeds that invade wilderness and other natural areas, but they can also kill or damage desirable native species. A great deal of effort has gone into developing application techniques or timing herbicide applications so that only targeted weeds will be killed. Examples include using cut-stump and basal bark methods of herbicide application on tree and shrub weeds like *Rhamnus catharticus* and *Ailanthus altissima*, and applying herbicides at a time of year when weeds like Japanese honeysuckle are green and photosynthesizing, but most native plants in the area are not.

Few Studies Quantify Impacts of Control Efforts on the Native Species and Ecosystem Process We Are Managing for

Unfortunately, relatively few studies have followed the impacts of wildland weed control on the recovery of the native species and ecosystem process managers sought to promote. Most have focused on whether the targeted weed was killed or suppressed. A noteworthy exception to this has been the extensive work by McEvoy and colleagues (1990; 1991; 1993a,b; Diehl and McEvoy 1990; James and others 1992) following impacts of the tansy ragwort (*Senecio jacobaea*) biocontrol program in western Oregon not only on the target weed, but also on native species abundance and diversity. Earlier research following the impacts of the Klamathweed (*Hypericum perforatum*) biocontrol program in the Pacific states also provided useful information on the recovery of native species (Huffaker and Kennet 1959). Similarly, Rice and colleagues' (1997) studied the impacts of herbicidal control of spotted knapweed (*Centaurea maculosa*) on the diversity and abundance of native species in western Montana grasslands and early seral forests. Fortunately, there are more studies of this sort underway, for example a five-year study of the impacts of large-scale herbicidal fennel (*Foeniculum vulgare*)control on the native plants, insects and herptiles on Santa Cruz Island, CA. However, land managers need to keep urging researchers to focus even more attention on the impacts of weed control efforts on the native species they seek to promote. In this regard, we can follow the lead of the agricultural community, where most weed control research is clearly focused on the ultimate goal in that realm - increasing crop production.

What Do We Still Need to Do and Know to Better Manage Invasive Wildland Weeds?

Despite a strong upsurge in awareness and actions to control invasive wildland weeds over the past decade, the problem continues to get worse. There are so many species of nonnative plants established in most natural areas that wildland managers will never have enough resources to control or contain them all. Therefore, there is a need for the development of weed management strategies that will efficiently and effectively address the most pressing problems. To implement these strategies, land managers will need better ways to prioritize their invasive weed problems. And to do this they will need better information on the ecological impacts of different invasive weeds, which ones can cause significant damage and which ones are relatively harmless, even if conspicuous. They need more information on the likely impacts of control on the weeds and the native plants and animals they want to protect. They need to know how to detect and map weeds over the large landscapes that they manage. They also need to know what steps they can take to prevent or slow invasions by new species and how to most quickly detect and contain new invaders. And they need good decision systems to help them synthesize all of this information and set logical priorities. Fortunately, work has begun on many of these fronts.

Adaptive Weed Management

Many land managers have begun using an 'adaptive strategy' for weed management. This is based on the precepts of adaptive management widely publicized and refined by Holling and Walters (Holling 1978; Walters 1986; Walters and Holling 1990). Randall and Robison (in prep) describe this as: 1) establishing management goals and objectives for the site; 2) identifying species that block you from reaching these goals and assigning them priorities based on the severity of their impacts; 3) selecting methods for controlling harmful species or otherwise diminishing their impacts and, if necessary, reordering priorities based on likely impacts of control on target and nontarget species; 4) developing and implement weed control plans based on steps 1-3; 5) monitoring the results of management actions; and 6) evaluating this information in light of the overall goals and objectives for the site and using this information to modify and improve control priorities, methods and plans, starting the cycle again. While use of this type of strategy is becoming more common, it is still too early to tell whether it will significantly improve weed management on the ground.

Setting Management Priorities

An important step in any comprehensive weed management program is setting priorities. This is often difficult because there are usually many invasive species and many invaded areas in a given wildland, and it can be difficult to collect and synthesize all the information necessary to set priorities. Hiebert and Stubbendieck (1993) developed and continue to improve upon a simple system (Hiebert 1997) designed to help land managers prioritizing invasive in logical step-by step fashion. This system in now available on the internet: http://www.ripon.edu/faculty/beresk/aliens/. But it will become more useful as information about the impacts of various species and of various control programs improves.

Quantifying Impacts of Weeds and Weed Control on Wildlands

A relatively small number of studies have clearly documented how certain weed species degrade the natural areas that they invade. Documented impacts include alteration of ecosystem functions like nutrient cycling, intensity and/or frequency of wildfires and hydrology, outcompeting and displacing native plants and animals and hybridizing with native species. Unfortunately, the impacts of many invasive species have not yet been clearly demonstrated. Experimental documentation of how well weed control programs work to restore native species and communities is even harder to find. These questions and information needs provide exciting challenges and opportunities for collaboration between weed scientists, conservation biologists and ecologists.

Mapping Wildland Weeds

Setting weed management priorities and assessing the impacts of control actions can be extremely difficult without accurate information on where the weeds are and whether their populations are spreading or contracting over time. Maps can fill this information gap but can be expensive and time-consuming to create, especially when the site is large. Several research groups have had some success accurately mapping selected wildland weeds, including leafy spurge, tamarisk, yellow hawkweed and yellow starthistle using images taken from airplanes (Birdsall and others 1997; Carson and others 1995; Everitt and others 1995, 1996; Lass and others 1996.). Progress has also been reported with the use of Global Positioning Systems and geostatistics to accurately map weed infestations (Child and de Waal 1997; Donald 1994; Webster and Cardina 1997). These techniques could significantly improve the coordination and success of wildland weed management in many areas, but their use is unlikely to become widespread until they become more affordable.

Improving Control Methods

There is, of course, also a great need for better control techniques. Methods that will kill or suppress only the targeted species while leaving all other species unharmed would be ideal, but we will likely have to settle for less in many cases. One of the greatest differences between management of weeds on wildlands and agricultural lands is this desire for extreme specificity of control techniques. This means that we need to place great importance on how various control techniques affect other nontarget species. Even biocontrol, in some cases the most specific tool available, should be studied more carefully for nontarget impacts.

Can Native Insects and Pathogens Control Some Weeds?

There is some hope that some nonnative weeds will eventually be brought under control by native insects and pathogens that adapt to feeding on them. It has been hypothesized that some species introduced to new areas do not become invasive, or at least do not attain pest status, because they are attacked and kept in check by pathogens, parasites and predators (including herbivores) native to the new area. In most cases where this phenomenon is known or suspected, the introduced species never escaped control or became a pest. It is possible, however, that native species might not begin to feed on a new invader for decades or centuries, long after it has become established and abundant in the new land. In fact, many land managers hold out hopes that some of the weeds that plague them will someday be turned on by native herbivores and pathogens. One of the very few instances where this appears to have happened involves the native weevil (*Euhrychiosis lecontei*), which is known to feed on the nonnative Eurasian watermilfoil (*Myriophyllum spicatum*; Sheldon and Creed 1995, Creed and Sheldon 1995). Significant impacts of this feeding were first noted only in this decade, and control of Eurasian watermilfoil attacked by the weevil remains irregular—satisfactory in some years, barely noticeable in others. The weevil may also cause watermilfoil to crash by early August, but the insect itself then becomes inactive, and watermilfoil may resurge dramatically by September.

The circumstances that allow this kind of "host-switching" of native species onto nonnative pests may occur only rarely. Nonetheless, it might prove extremely useful to learn more about what these circumstances are and whether there are ways to promote them. It would also be useful to know whether we might expect the likelihood of such host-shifting to increase with time and, if so, over what time-scale.

Preventing New Invasions

Basic research on invasiveness and invasiblity can provide some help. The better our ability to predict which species are most likely to invade and become pests, the easier it will be to work with the nursery industry and other groups interested in importing new plant species to screen out at least a few of the likely bad actors. Greater knowledge of what makes a site prone to invasion may help managers set priorities for inventory and management activities. Unfortunately, we might get the most information about invasiveness and invasibility from experiments that are too dangerous and unethical to contemplate seriously: studies in which new species were intentionally released and observed as they spread or died out over time.

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