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Author(s): Kirk W. Davies and Dustin D. Johnson
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Are We "Missing the Boat" on Preventing the Spread of Invasive Plants in Rangelands?

Kirk W. Davies and Dustin D. Johnson*

Invasive plants are negatively affecting the ecological and economic production of rangelands by reducing resource productivity, decreasing biodiversity, displacing native vegetation, and altering ecosystem processes and functions. However, despite these well-known negative effects, once invasive plants are regionally established, limited effort is directed at preventing their continued spread across rangelands. Most efforts are directed at restoration at specific locations while additional rangelands are invaded. Restoring native plant communities invaded by exotic plants is frequently unsuccessful, especially in more arid environments, and is often too costly to apply at the scale required to make meaningful progress in reducing invasive plant populations relative to their expansion. Of the few prevention efforts being implemented, most are a second priority to control and restoration efforts. Integrating strategies to prevent new infestations and restrict the expansion of existing populations in invasive plant management programs is critical to limiting the negative effects of invasive plants in rangelands. However, we are "missing the boat" on this issue by not providing sufficiently developed and validated management actions. Limited information is available for developing management strategies to prevent the spread of invasive plants, although it has been suggested that land managers need to increase biotic resistance of desired plant communities, decrease invasive plant propagule pressure, and eradicate small incipient infestations to prevent the continued expansion of invasive plants. Thus, instead of scientifically validated methods developed to limit the spread of invasive plants, managers are often left with vague suggestions for preventing the continued spread of invasive plants. We suggest that if prevention is going to be successful, researchers are going to need to conduct more applied research to provide land managers with specific prevention strategies and quantify the benefits of various prevention strategies.

Key words: Applied research, conservation, dispersal, invasion, land management, resistance.

Invasive plants decrease biodiversity, reduce production, eliminate key wildlife habitat, displace native species, and alter ecosystem processes and functions (Davies and Svejcar 2008; DiTomaso 2000; Kolb et al. 2002; Masters and Sheley 2001; Pimm and Gilpin 1989; Randall 1996; Wittenberg and Cock 2001). This includes the alteration of historical disturbance regimes by exotic plant invasions, which can be detrimental to native vegetation and fauna (Brooks et al. 2004; D'Antonio and Vitousek 1992; Davies and Svejcar 2008;). Societal costs of invasive plants are extremely large. Invasive plant species not only diminish the productivity and ecological services of nonarable lands, but restoration is expensive and often unsuccessful after invasion. In 1994 in the United States, the negative impacts of invasive plants species were estimated to be $13 billion a year (Westbrooks 1998). Pimentel et al. (2000) estimated exotic species, including invasive plants, were responsible for economic and environmental losses of about $137 billion in 2000. Furthermore, efforts to control invasive plants can at times exacerbate the negative effects of the invader (Pearson and Callaway 2008; Rinella et al. 2009). Perhaps even more alarming, some of the negative impacts of invasive species are irreversible, such as native species extinctions (Pimentel et al. 2005).

The continued increase in acreage infested by invasive plants suggests large improvements are possible in our approach to invasive plant management in rangelands. For example, yellow star-thistle (*Centaurea solstitialis* L.) is spreading at a rate of $> 135{,}165$ ha yr^{-1} in California (Pitcairn et al. 2006), medusahead [*Taeniatherum caput-medusae* (L.) Nevski] more than doubled the area it occupied in Idaho between 1957 and 1992 (Hironaka 1994), and spotted knapweed (*Centaurea stoebe* L.) has increased the area it infests at about 27% per year between the 1920s and early 1990s (Sheley et al. 1996). The

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* Rangeland Scientist, U.S. Department of Agricultural–Agricultural Research Service, Eastern Oregon Agricultural Research Center, 67826-A Hwy. 205, Burns, OR 97720; Assistant Professor, Oregon State University, Department of Rangeland Ecology and Management, Harney County Extension Office, 450 N Buena Vista #10, Burns, OR 97720. Corresponding author's E-mail: kirk.davies@oregonstate.edu

continued spread of invasive plants is probably the product of reactionary management not being able to effectively limit the expansion of exotics. The underlying problem with conventional reactive invasive plant management approaches is that once invasive plants have established rapidly spreading populations, control is extremely expensive and time consuming (Huenneke 1996), and eradication is probably no longer an option (Eiswerth and Johnson 2002; Mack et al. 2000).

However, even if invasive plants are effectively controlled, desirable vegetation must often be reestablished to have long-term benefits. Revegetation after invasive plants have been controlled is often difficult and can be especially problematic in more arid environments such as the Great Basin, southwestern deserts of the United States, and the deserts of Africa, Australia, and Asia. Revegetation of some sites with native plant species could be improbable because restoration of native vegetation in areas infested with invasive plants is rarely successful (Vitousek et al. 1997), and native plants might be prohibitively expensive or simply unavailable for restoration projects (Davies and Svejcar 2008). Invasive plants can also alter physical or chemical soil properties and develop a persistent invasive plant seed bank, making restoration even more challenging (D'Antonio and Meyerson 2002). Site alterations by invasive plants might make it improbable that the native plant community can reclaim the site, even if the invasive species is eradicated (Cronk and Fuller 1995; D'Antonio and Meyerson 2002). Another potential problem with restoration is that restorative activities can have undesirable impacts on the environment, particularly when activities alter the soil profile (Papanastasis 2009).

The general failure to limit the spread of invasive plant species and inherent challenges and risks associated with efforts to restore native plant communities postinvasion suggests an urgent need to place more emphasis on integrating effective prevention strategies into invasive plant management. Although prevention does not eliminate the need for control and restoration of already invaded plant communities, it is critical to implementing successful invasive plant management programs (Davies and Sheley 2007; DiTomaso 2000; Rejmànek 2000; Sheley et al. 1996). Adopting a preventative approach to managing invasive plant species has the potential to preclude the need for restoration of millions of nonarable hectares.

Despite the obvious benefits of limiting the expansion of invasive plants, prevention is largely underutilized in invasive plant management. Prevention efforts are currently underfunded (Leung et al. 2002; Pimentel et al. 2005), with resources invested primarily on control rather than prevention (Finnoff et al. 2007). A few efforts have been implemented, such as requiring weed-free certified hay in specific areas, but comprehensive prevention efforts are generally lacking. Thus, although the literature (e.g., Davies and Sheley 2007; DiTomaso 2000; Mack et al. 2000; Rejmànek 2000; Sheley et al. 1996) is clear that prevention should be a priority, it often is not. The limited use of prevention in invasive plant management could be the product of a general lack of information detailing successful prevention strategies, propensity of humans to be more reactive than proactive, lack of funding, and uncertainty of the productivity of applying prevention. Most prevention discussions commonly revolve around general guidelines, not actual strategies and tools for the implementation of a successful prevention program (e.g., Sheley et al. 1999;). Prevention is also probably underutilized because research rarely focuses on developing prevention management tools. Instead, most invasive plant research focuses on the control and impacts of exotic plants or the ecology of invasion without any strong ties to management. Finnoff et al. (2007) demonstrated that prevention is often not applied because managers cannot be certain of the productivity of prevention efforts, whereas there is less uncertainty with control. In other words, acreage of invasive plants that have been controlled is easily measured and reported and, therefore, less abstract than an undetermined decrease in risk of invasion with prevention efforts. Thus, decreasing the uncertainty associated with the productivity of prevention efforts should also increase the use of prevention measures.

Basic suggestions for prevention management include decreasing propagule pressure, maintaining or increasing plant community biotic resistance to invasion, and eradicating small invasive plant satellite populations (Davies and Sheley 2007; Mack et al. 2000). However, management actions based on these suggestions for prevention have rarely been tested, and we suggest that invasive plant prevention would be more widely adopted and successful if the effects of prevention efforts were quantified. This would also remove some of the uncertainty about the productivity of prevention. We propose that applied research focused on these three suggestions for prevention management is needed to develop and test specific management actions to prevent the continued spread of invasive plants. Some of this research will have to be specific to particular invasive plants in set geographical areas to be meaningful.

Decreasing Invasive Plant Propagule Pressure

Propagule pressure by invasive plants is a prerequisite for invasion to occur. Simply, if invasive plant propagules are not present (i.e., no propagule pressure), invasion will not occur. Levine et al. (2003) speculated that given sufficient propagule pressure, few native plant communities could remain noninvaded. Thus, as invasive plant propagule pressure increases, so does the probability that invasion will occur, assuming abiotic factors are not the limiting factor to invasive plant establishment and survival. Consequently, reducing invasive plant propagule pressure decreases the probability of invasion (D'Antonio et al. 2001; Davies 2008; Davies et al. 2008).

Although most invasive plant control programs on rangelands reduce propagule pressure by decreasing the population of invaders or their ability to reproduce, few programs implement strategies explicitly designed to decrease propagule pressure. Specifically lacking are studies focused on reducing propagule pressure on noninvaded rangelands from invaded rangelands (however, see Davies et al. 2010). Because propagule pressure could be the most important factor determining the success of invasive species, there are opportunities to enact strategies to lessen invasive species propagule pressure to improve efforts to protect native communities at local levels (Reaser et al. 2008). A major limitation to largely eliminating invasive plant propagule pressure is the lack of validated management actions developed for specific invasive plants or groups of invasive plants and then quantification of the benefits of implementing these actions.

Land managers would be more inclined to adopt strategies to prevent the spread of invasive plant propagules if their success and cost effectiveness has been clearly demonstrated. Thus, identifying the various vectors that disperse an invasive plant and then testing the effectiveness and cost efficiency of different management actions for reducing dispersal by each vector represents a critical need in the field of invasive plant management. Studies investigating combinations of strategies to limit dispersal by several vectors would also be valuable.

Maintaining or Increasing Biotic Resistance

Biotic resistance of a plant community is its ability to limit the invasion of exotic plant species. The biotic resistance of a plant community to invasion is important to preventing invasive plant species spread. If invasive plants are dispersing to locations with abiotic conditions suitable for completion of their life cycle, then biotic resistance is the primary obstacle to preventing successful invasion.

The biotic resistance of a plant community to invasion is influenced by plant species diversity and abundance, species dominance, site characteristics, herbivory and other disturbances, and the interaction between these factors. These factors influence biotic resistance by controlling the availability of resources and safe sites for invasive plants. Increases in resource availability generally increase the invasibility of plant communities (Bakker and Berendse 1999; Kolb et al. 2002; Milchunas and Lauenroth 1995; Wedin and Tilman 1996; White et al. 1997). High resource availability has also been demonstrated to increase the competitive abilities of invasive plants over native plants (Claassen and Marler 1998; Kolb et al. 2002; Nernberg and Dale 1997; Vasquez et al. 2008; Wedin and Tilman 1993).

However, this information needs further refinement to be practical for developing plans to manage the biotic resistance of plant communities. Some of the information can be confusing because of mixed and even contradicting results. For example, diverse plant communities have generally been assumed to have greater biotic resistance to invasion than less diverse plant communities because negative correlations have been reported between invasive and native plant diversity (Brown and Peet 2003; Elton 1958; Knops et al. 1999; Levine 2000; Tilman 1997). However, at larger spatial scales, greater diversity in plant communities has been correlated to increased diversity of exotic plants (Lonsdale 1999; Stohlgren et al. 1999, 2003). The relationship between diversity and invasibility is probably confounded by some plants having disproportionate influence on invasibility. For example, disturbances that damage dominant species can decrease plant community biotic resistance more than disturbances that do not negatively affect dominant species (Burke and Grime 1996).

Although limited, a few studies have evaluated the influence of some management actions on the biotic resistance of plant communities. For example, Davies et al. (2009) demonstrated that long-term grazing exclusion, compared with moderate levels of grazing, allowed an accumulation of fuels that, when burned, decreased the biotic resistance of sagebrush–bunchgrass plant communities to exotic annual grass invasion. Pokorny et al. (2005) demonstrated that the loss of perennial forbs from native communities decreased the resistance of the plant community to invasion by an exotic perennial forb. Previous research has mainly elucidated factors that have deleterious effects on biotic resistance. Other than Davies et al. (2010), who demonstrated that seeding a competitive nonnative perennial bunchgrass could increase the biotic resistance of plant communities to exotic annual grass invasion, few studies have investigated methods to increase biotic resistance in established plant communities. Research determining how different management strategies influence biotic resistance and what strategies are most effective against specific invasive plants are critically needed. Quantifying the biotic resistance of various stable states of rangeland plant communities would be extremely valuable; thus, managers could determine whether they needed to facilitate succession to a more biotic-resistant stable state to decrease the risk of invasive plants invading a specific plant community.

Eradicating Small Infestations

Most programs currently in place for detecting and eradicating invasive plants are for new invasive plants at regional or national levels. For example, the National Early Detection and Rapid Response System for Invasive Plants was developed for the management of new invasive plants in the United States (Westbrooks 2004). However, land managers are often challenged with invasive plants that are already present and too widespread for regional or national eradication. However, small individual infestations could still be targeted for eradication, even though the invasive species probably will not be eradicated regionally or nationally. Eradicating small infestations is critical because unpredictable events could lead to new invasions despite a small probability of invasion resulting from limited propagule pressure and high biotic resistance. The establishment of small infestations can transform an area that previously experienced low invasive plant propagule pressure into an area with high propagule pressure. Focusing on small infestations when eradication is still possible will protect many hectares from invasion and, thus, should be an integral component of invasive plant management.

To improve the odds of successfully eradicating new invasive plant infestations, they should be located while they are still relatively small. Early detection can make the difference between eradication and long-term financial commitments to controlling the invasive species (Rejmánek 2000). Eradication efforts are often restricted to infestations smaller than 1 ha (DiTomaso 2000), although larger scale eradication projects can be accomplished (Pokorny and Krueger-Mangold 2007; Rejmánek and Pitcairn 2002). Inventory and eradication of small invasive plant infestations is a more effective strategy than controlling large infestations (Moody and Mack 1988; Smith et al. 1999). Thus, strategically inventorying and monitoring lands for incipient infestations is of paramount importance.

However, searching for new infestations across entire landscapes would probably be untenable and prohibitively expensive; thus, development of effective and cost-efficient strategies to locate new infestations is critical for success. For example, Bradley and Mustard (2006) developed a risk assessment map of future annual grass invasion based on landscape dynamics of invasion that could be used to help prioritize areas that need to be monitored for new infestations. Additional studies are needed to validate and improve risk assessment maps. Advancements in technology, especially remote sensing, could improve the ability to detect new infestations when they are still small enough for eradication. Hyperspectral images are the most commonly used images to remotely detect invasive plants (Huang and Asner 2009) but have had varying levels of success at detecting invasive plants (Hestir et al. 2008; Lass et al. 2005). Remote sensing of invasive plants is possible, but its efficacy for detecting small infestations is currently constrained by costs, a limited ability to detect low-density or subcanopy infestations, inconsistencies in invasive plants' spectral signatures, and, at times, an absence of adequate separation in spectral signatures among plant species with the use of current technologies (Hestir et al. 2008; Huang and Asner 2009; Lass et al. 2005). Advancements in remote sensing tools will undoubtedly improve our ability to detect small invasive plant infestations.

The other critical component of early detection and rapid response is successfully eradicating satellite populations. Additional research efforts determining the success of various practices for eradicating satellite invasive plant populations are needed. A protocol with treatments and monitoring and retreatment requirements needs to be developed to ensure that satellite populations targeted for eradication are actually eradicated.

Conclusions

The general lack of research in developing prevention tools and strategies is alarming. Although the importance of prevention is widely accepted, most research focuses on restoration and controlling invasive plants or investigating the ecology of invasion. A good example of the lack of priority assigned to prevention is the several peer-reviewed journals dedicated to restoration, whereas none focus on preventing exotic invasions. Resources are allocated primarily to controlling existing infestations rather than preventing new infestations (Finnoff et al. 2007). More resources and efforts need to be allocated to developing effective dispersal prevention strategies (Davies and Sheley 2007), determining how to enhance and maintain the biotic resistance of plant communities to invasion, and increasing the efficiency of locating and eradicating satellite infestations. The ability of land managers to prevent the spread of invasive plants is limited by a deficiency of applied research that has developed and validated management actions to limiting exotic plant invasion. Thus, for prevention to be more successful and widely adopted, research needs to place a high priority on developing better tools and strategies for decreasing propagule pressure, increasing biotic resistance, and detecting and eradicating new infestations earlier. Prevention is currently underfunded, and a much higher level of funding is warranted (Leung et al. 2002). Demonstrating the effectiveness and quantifying the benefits of specific prevention strategies would encourage wider adoption of prevention practices and subsequently protect the biodiversity and function of native plant communities.

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