Invasive plants in wildland ecosystems: merging the study of invasion processes with management needs

Carla M D'Antonio[1], Nelroy E Jackson[2], Carol C Horvitz[3], and Rob Hedberg[4]

Increasing numbers of non-native species threaten the values of wildland ecosystems. As a result, interest in and research on invasive plant species in wildland settings has accelerated. Nonetheless, the ecological and economic impacts of non-native species continue to grow, raising the question of how to best apply science to the regulation and management of invasive plants. A major constraint to controlling the flow of potentially undesirable plant species is the lack of a strong regulatory framework concurrent with increases in trade volume. To address this, ecologists have been developing models to predict which species will be harmful to wildland values and are working with the horticultural industry to apply this information to the sale of species. The management of established invasive plants is hampered by conflicting goals, a lack of information on management outcomes, and a lack of funding. Ecologists and weed scientists can provide a scientific basis for prioritizing species for control and for managing species composition through the application of control technology, which can take place simultaneously with the manipulation of the ecological processes that influence community susceptibility to invasion. A stronger scientific basis for land management decisions is needed and can be met through nationally funded partnerships between university and agency scientists and land managers.

Front Ecol Environ **2004; 2(10): 513–521**

Increasing numbers of invasive plant species affect the multiple values of traditional managed lands and less intensively managed systems. While their potential ecological importance was noted by ecologists throughout the 20th century (eg Elton 1958), it has only been in the past decade that invasive species have been intensively studied outside the realm of agriculture. The continued fragmentation and increased recreational use of wildlands, pervasive environmental changes, and our evolving awareness of the interconnectedness of landscape elements have led to a blurring of the distinctions between natural and managed ecosystems. The distinctions between applied and basic ecology have become blurred as well; ecology increasingly addresses issues of direct societal concern, such as invasive species, while traditionally narrowly defined, applied research such as "weed science" is being used in more ecological settings. These shifts have resulted in an explosion of research on invasive species. At the same time, however, the magnitude of land-cover change and the impacts of invasive species have continued to grow.

In a nutshell:

- Increasing numbers of invasive plants threaten the benifits we acquire from wildland ecosystems
- Increased international trade and travel and limited regulatory capacity allow potentially harmful plant species to be imported and moved around the US
- New scientific tools are being developed that can influence the introduction, sale, and spread of invasive species and provide a basis for making decisions between management options
- While scientific studies of invasion are now commonplace, challenges remain in designing experiments to inform land management and transforming weed control from killing weeds to a broader ecosystem focus

Recognizing the overlap in their interests, the Ecological Society of America (ESA) and the Weed Science Society of America (WSSA) and the organizing committee of the 7th meeting on Ecology and Management of Alien Plant Invasions (EMAPI 7) organized a conference in November 2003, which focused on the science and management of invasive plants. Attended by over 800 people, the conference goals included the sharing of recent research advances and discussion of research-related management needs. It was clear from this and other recent meetings of the ESA and WSSA that the amount of university-based research on invasive species in wildlands has skyrocketed. At the same time, more funding than ever before is being directed towards invasive species management in wildlands. Yet undesirable invasive plants continue to spread (Figure 1), raising questions about the role that scientists can play in managing such species.

[1]*USDA–ARS, 920 Valley Road, Reno, NV (dantonio@es.ucsb.edu);* [2]*Monsanto Corporation (retired), Corona, CA;* [3]*University of Miami, Department of Biology, Coral Gables, FL;* [4]*Weed Science Society of America, 900 Second Street NE, Washington DC*

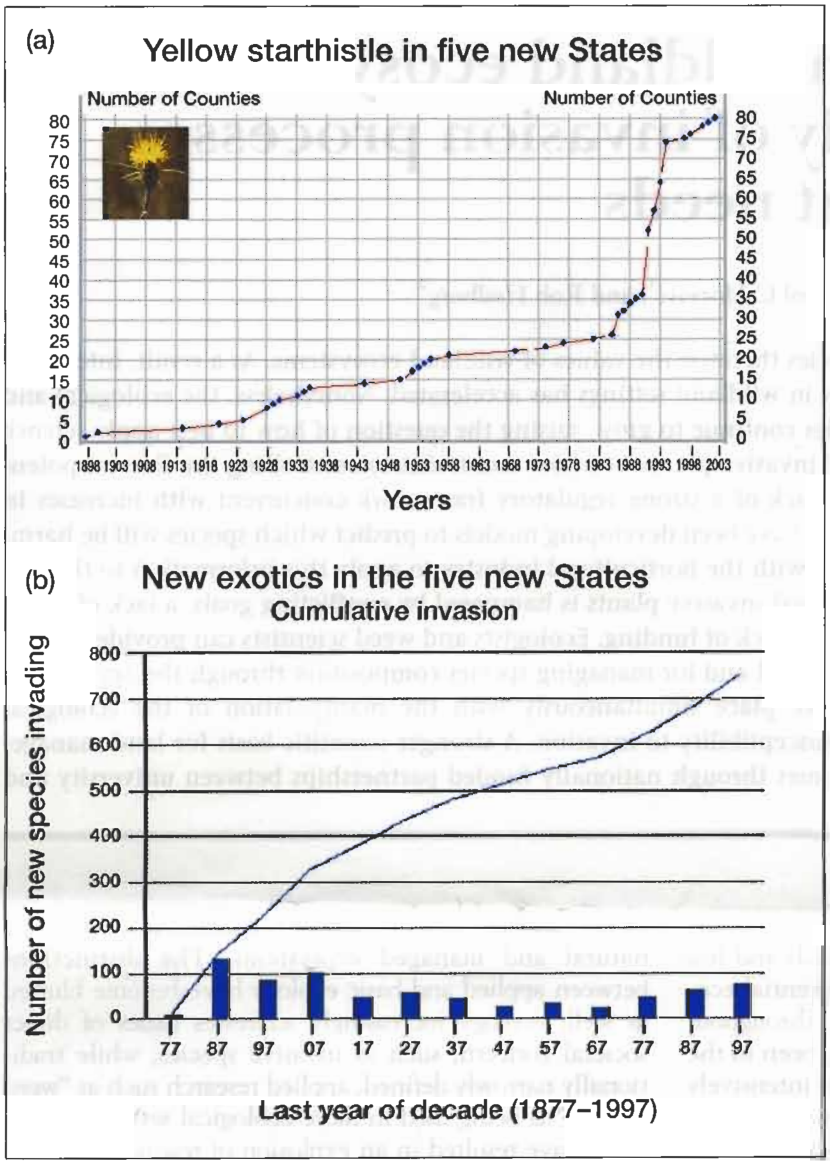

Figure 1. *(a) Expansion in the number of counties reporting occurrence of yellow starthistle* (Centaurea solsticialis) *in the five northwestern States (Washington, Oregon, Idaho, Montana, and Wyoming). Data are from herbarium records compiled by P Rice, (Department of Biological Sciences, University of Montana, Missoula MT, INVADERS database system, http://invader.dbs.umt.edu/). (b) Appearance of "new" non-native species in the five northwestern States in 10-year increments for the past century. (Data compiled by P Rice).*

Here we discuss some enduring challenges and new directions that have emerged in invasive species research, including some difficulties incorporating science into regulation and the control of non-native plants. Rather than providing a detailed description of research needs, we attempt to contribute to the mind-set shift needed to curb expansion of this problem. As a framework, we use Lonsdale's (1999) simple equation predicting the number of non-native species in an area, $E=I \times S$, where E is the number of exotic species established in an area, I represents the number of species introduced, and S is their survival rate. We first focus on some of the impediments to controlling "I" – that is, regulating the importation and movement of species. We then discuss challenges in the application of science to the management of established invasive plants as it affects "S".

■ Science and policy related to the introduction of potentially harmful species

A number of studies have argued that preventing the entry of a harmful species is the most cost-effective and ecologically desirable approach (Naylor 2000; National Invasive Species Council 2001; Leung *et al.* 2002). Prevention is hampered, however, by the lack of a strong regulatory framework, the rapidity with which some species can spread, and the reality of increasing world trade and travel.

Strengthening the regulatory framework

Most invasive and damaging wildland plant species have gained entry to the US through the nursery industry or as other deliberate introductions; there is little regulation of which plant species are imported (US Congress 1993; NRC 2002). The most important legislation regulating plant importations is the Plant Protection Act of 2000, which authorizes the Secretary of Agriculture to regulate the importation, interstate transport, selling, purchasing, giving, or receiving of any noxious weed (defined as "any plant or plant product that can directly or indirectly injure or cause damage to crops [including nursery stock or plant products], livestock, poultry, or other interests of agriculture, irrigation, navigation, the natural resources of the USA, the public health, or the environment"). Despite the broad authority of this Act, it covers only those 96 species listed under the Federal Noxious Weed Act (Public Law 93-629, January 1975), the only plant species that cannot be imported legally into the US. There are, on the other hand, at least 300 damaging wildland plant invaders nationwide that are not listed as noxious weeds (NRC 2002).

Many important legislative and societal barriers to changing regulations or adding more species to the federal noxious weed list persist (Miller 2004; Miller and Gunderson 2004). Nevertheless, ecologists and weed scientists can provide some of the quantitative assessments needed to get species formally listed as noxious weeds and provide a scientific basis for policy decisions as the demand for regulatory reform increases. Executive Order 13112, issued by President Clinton in 1999, established the National Invasive Species Council. This, along with the increased number of both state and national bills that mention invasive species, suggests that lawmakers are beginning to recognize the need for such reform.

Working with the horticultural industry

Horticultural imports into the US have risen dramatically over the past 20 years (Figure 2) and the origin of imports has increasingly shifted to new regions (NRC 2002). At a 2001 meeting, nursery representatives and scientists reviewed the state of the science related to prediction and drafted a voluntary code of conduct for the industry and for landscape architects, to prevent further sale and spread of ecologically damaging species (St Louis Declaration, www.centerforplantconservation.org/invasives/). Such codes rely on scientists communicating with the industry at local, regional, and national scales to provide quantitative evidence for "harm", identify environments that are at risk, and provide acceptable alternatives. Scientists in Florida have helped the nursery industry establish protocols to evaluate the potential for ecological damage from plants currently in trade, in order to phase them out (www.fleppc.org/FNGA/FNGA_Pressrelease.htm). Similar interactions between science and policy have occurred in New Zealand, where some of the most stringent laws are in place to regulate plant importations (ie Biosecurity Act of 1993) and where scientists are developing models to screen invasive plants (Pheloung *et al.* 1999). World Trade Organization regulations liberalized trade in the 1990s, making it harder to ban species from international trade because regulations must be based on science (USDA/FAS 1999), thereby increasing the need for additional research.

The ability to spread rapidly is the first step towards recognizing a plant that may be of concern. A concerted scientific effort has been devoted to identifying plant traits that predict which species are likely to be invasive once introduced (eg Newsome and Noble 1986; Rejmanek 1996; Rejmanek and Richardson 1996; Reichard and Hamilton 1997). The results suggest that there are no specific traits that alone predict invasiveness (NRC 2002). Rather, the best single predictor is what a species has done in other places (Reichard and Hamilton 1997; NRC 2002). For this to be useful there must be reliable taxonomic identification, communication among agencies, and ready access to informative databases. Impressive progress has been made on the database front (Table 1). However, there is very little historical data on the many hundreds of new species entering the horticultural trade each decade. The task of trying to predict the invasive behavior and impacts of dozens of plants previously unknown to this country is daunting. In addition, genetic changes occurring after introduction can complicate the issue (Figure 3). In Hawaii, efforts are being made to provide a screening mechanism for plant importations, based on the approach of Pheloung *et al.* (1999), using a list of questions about plant traits and species ranges

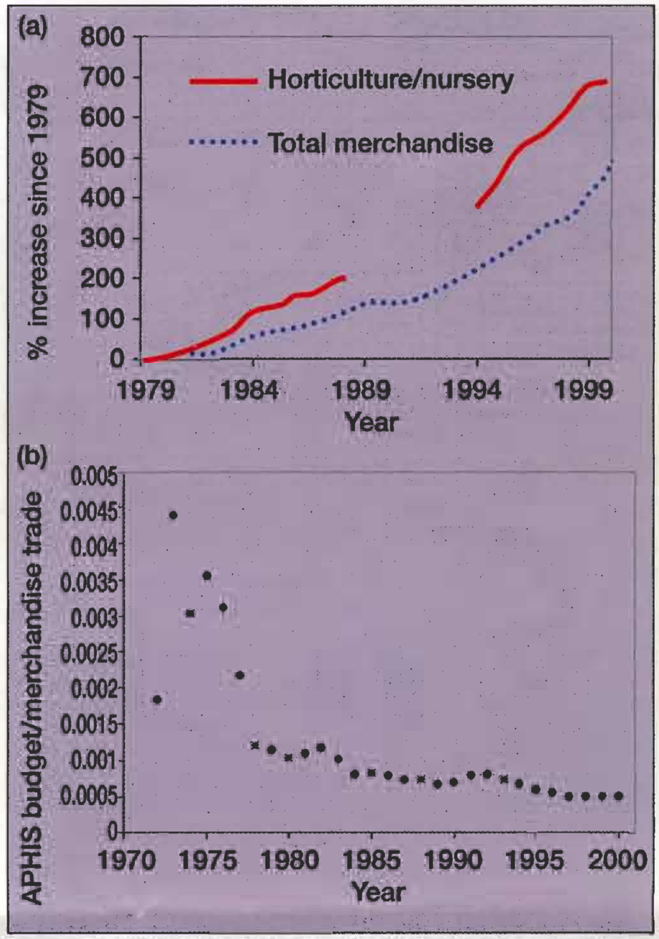

Figure 2. *(a) Increasing rates of trade in the horticultural and nursery stock industry in comparison to changes in total merchandise import volume. Values are normalized by the 1979 trade volume for nursery stock as presented in US dollars. Data are from US Department of Commerce, Bureau of the Census, Foreign Trade division and are published at www.stat-usa.gov and www.census.gov/foreign-trade/statistics. (b) Total annual APHIS budget as a function of volume of importation into the US over the period 1971–2000. APHIS budget figures were derived from Government publications and Trade volume was derived from figures provided by the US Department of Commerce, Bureau of the Census, Foreign Trade Division (www.census.gov/foreign-trade/statistics/).*

(Daehler *et al.* 2004). Its use so far has only been retrospective. However, use of trait- and history-based models that are region-specific may be the most effective approach for applying predictive science to the horticultural industry in the current regulatory environment.

Inspection and early detection

Several economically and ecologically important weeds entered the US as contaminants in commodity shipments (US Congress 1993). Regulation of potential contaminants has been the responsibility of the US Animal and Plant Health Inspection Service (APHIS), but funding for APHIS has not kept up with the increase in vol-

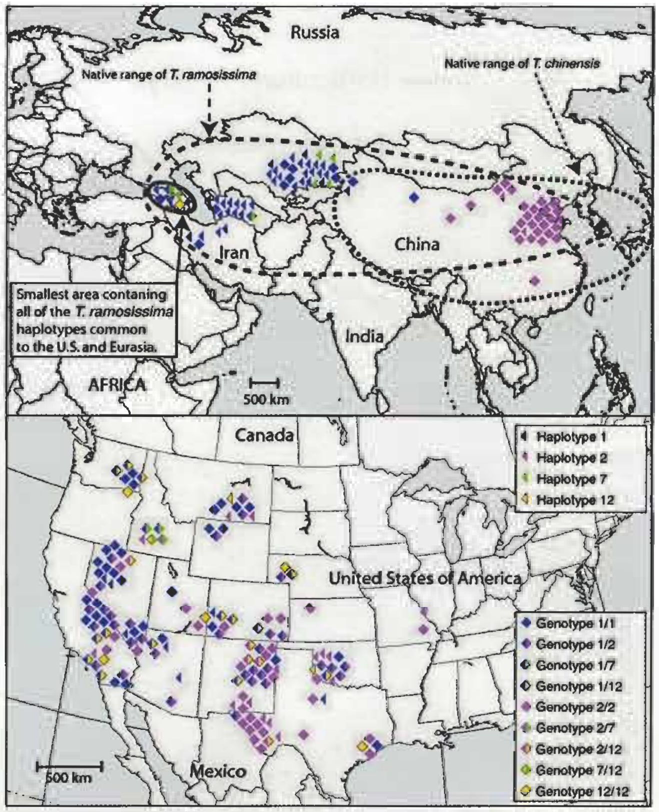

Figure 3. *Maps showing extensive hybridization of two* Tamarix *(tamarisk, or salt cedar) species after introduction into the US from Europe and Asia. The now dominant form of invasive* Tamarix *in the intermountain west appears to be a hybrid formed after introduction. The following is taken from Gaskin and Schaal 2002: "Approximate distribution of* T chinensis *and* T ramosissima *haplotypes and genotypes common to Eurasia and the US in their native range (above) and in the US (below). Locations of specimens are spread out on the map to avoid overlapping. Bold circle indicates smallest Eurasian area that contains all* T ramosissima *haplotypes common to the US and Eurasia. Dashed circles indicate native range of species sensu Baum." (Reprinted with permission from the Proceedings of the National Academy of Sciences (PNAS).*

ume of imports (Figure 2) and APHIS personnel can only inspect roughly 2% of the ships, planes, people, and cargo coming into the US (USDA/FAS 1999). APHIS' Port Inspection activities are therefore being severely challenged by increasing levels of trade and travel. Identification of the most likely pathways of entry of harmful species will help to target scarce resources.

Scientists and managers have documented that roads, vehicles, and movement of crops and commodities provide a means of dispersal for established weeds into new areas (US Congress 1993). Regulation of this flow, however, is often not feasible within the budgets of federal and state programs. Nonetheless, scientists can improve detection efforts by helping to provide user-friendly identification guides for both plants and seeds of concern, lists of species likely to be introduced, their probable pathways of introduction, and the habitats that may be invaded. The involvement of scientists in cooperative extension programs has been an important avenue for funneling appropriate research findings into management tools.

Table 1. Sample web sites that provide lists of potentially harmful, invasive plant species (websites were active as of November, 2004)

Web address	*General contents*
www.bbg.org/gar2/pestalerts/invasives/relatedlinks.html	Detailed listing of websites that contain information on invasive plants. Includes references to websites that deal with global, national, regional, and local "problem" species.
www.nps.gov/plants/alien/moreinfo.htm	Lists internet resources on invasive species. Provides access to a wide range of relevant websites.
www.invasivespecies.org/bonap/	Biota of North America, search species lists by state.
http://plants.usda.gov/	General plant database with state noxious weed lists for 36 states. Hoping to expand to county level data for all species.
www.issg.org/database	Global invasive species program database. So far, contains limited number of plant species but all places where they have been reported to be a problem.

■ Science and management of established species

The increasing collaboration between academic scientists and managers and the greater interest in using ecological principles to manage invaders in natural areas is encouraging (Sheley and Krueger-Mangold 2003). However, the challenges of integrating biology, ecology, management concerns, and control methods into science-based management programs are daunting. One fundamental reason is that scientific knowledge about the invasion process is slow to accumulate, and the nature of scientific inquiry is such that concrete advances are likely to be incremental. Meanwhile, managers need to take care of lands that are changing rapidly. An analogy might be the slow progress of scientific understanding of a disease as compared to the clinician's need to take care of patients who are its current victims.

Both scientists and managers are mainly concerned with a small fraction of the naturalized non-native species in any area. These are often

Figure 4. *(a)* Arundo donax *(giant reed), a large riparian grass, invades riparian ecosystems throughout lowland California. (b) It has contributed to bridge failure during floods, and (c) builds up enormous flammable biomass, but it is the sole source of clarinet reeds – which the farm in (c) is planted to produce – and is being investigated in the US and abroad as a source of fiber.*

termed "transformer species", defined as species that alter resources in such a way that land is no longer providing the same value as habitat for organisms or as a resource for society (Richardson *et al.* 2000). One necessary step is to determine which of the naturalized species in a location is behaving as, or is likely to become, a transformer species. Lack of clarity on this point has unfortunately led to inappropriate critiques of invasive species research (Simberloff 2003a).

Articulating goals

Setting goals related to invasive plant management must take into account the differing needs of a broad array of individuals, including policy makers, scientists, public land managers, private land owners, and often private industry. Even managers of county, state, and federal lands may have distinct mandates and concerns. The sharing of common goals is necessary for the development of effective regional plans for early detection of and response response to weed infestations and for regional control. From a scientific perspective, careful measurements of impacts together with quantification of the conditions under which particular species are likely to be threats, and how rapidly populations can grow and spread, can provide a basis for prioritizing species for control at both local and regional scales.

At a local scale, there is a need for a clear articulation of conflicting or distinct goals in a partnership of science and management. Ongoing dialogue during project realization can lead to recognition and then resolution of potentially conflicting goals or expectations. Science can inform managers about the probable outcomes of particular efforts, with alternative scenarios provided at the outset and along the way.

Goal definition is complicated by the difficulty of balancing economic costs against ecological benefits when controlling or ignoring particular species. Some species viewed as ecologically and economically damaging are also commodities (Figure 4). Assessment of non-market (ie ecological) values is contentious (Hausman 1993) but of increasing importance, necessitating stronger interactions with economists to help resolve contradictory goals. Recent publications on the economics of invasive species stress the role that economic models can play in incorporating both human values and ecological knowledge into risk-reduction strategies (Shogren 2000). This can justify the high costs of clearing or help to shape invasive species management programs (eg Turpie and Haydenrych 2000), as well as providing a rationale for biocontrol research and implementation programs (Hill and Greathead 2000).

Are managers aiming too low?

Simberloff (2003b) has argued that we are aiming too low in setting goals relative to the control and eradication of unwanted plant populations. He concludes that the paltry number of plant eradications is due as much to attitude and commitment as to our understanding of the biology of "weedy" plants. With regard to early detection and rapid response, complete *local* eradication would be the most important step to slow regional spread. Too often, potentially problematic species have been disregarded because they are not yet abundant, while small populations of well-established invaders are ignored because the species are viewed as hopeless problems. Yet an expanded concept of eradication, one that focuses on all scales (including the homeowner's backyard) would provide a basis for halting the spread and improving the control of many species. In the same way, multi-agency, cross-jurisdictional collaborations can lead to consistency, an important factor for goal attainment. Researchers can provide tools to ameliorate local populations, predict their potential resilience, and hone spatial and temporal approaches to eradication across different spatial scales.

■ Applying experimental results and embracing environmental variability

Ecological experiments tend to be done on a scale that is much smaller than a typical management unit (eg Figure 5) and their relevance to landscape management has been debated. For example, small-scale experiments generally show that increased diversity can lead to increased resistance of vegetation to invasion (eg Tilman 1997; Levine 2000; Naeem *et al.* 2000; Kennedy *et al.* 2002), a

***Figure 5.** Scale of research plot versus scale of removal/restoration effort in hardwood reserve in Miami-Dade County, FL. Managers believed that removal of exotic species, two of which are shown in (a) and (b), would facilitate post-hurricane recruitment of native forest species. (c) Researchers tested this hypothesis by establishing study plots in managed and unmanaged areas within three reserves. In managed areas exotic species were removed periodically; in unmanaged areas exotic species were allowed to proliferate for 5 years. These latter were the only areas that remained unmanaged, as management goals were not consistent with scattering exotic-rich plots throughout the reserve. Research plots (approximately 30 x 60 m in size) therefore sampled only a small portion of the reserve, not the ideal from a research perspective. In this particular case, there was sufficient small-scale heterogeneity (at the 5 x 5 m scale) within each of the research plots (managed and unmanaged) at the onset of the experiment to justify an experimental design that considered a subplot scale unit of analysis. Research results supported the hypothesis that removal of exotic plants improved regeneration of native species following hurricane damage. Results are described in Horvitz and Koop (2001).*

finding of importance to restoration practitioners. However, at the landscape scale, the correlational, non-experimental relationship between the diversity of native and exotic species tends to be positive (Levine and D'Antonio 1999; Lonsdale 1999; Stohlgren *et al.* 1999, 2003). This has led to much debate about the value of small-scale experiments relative to the management of large units (Stohlgren *et al.* 2003).

Spatial population dynamics includes two major components: increase in populations at local points (measured by λ, the rate of population growth), and spread of populations across the landscape (measured by c^*, the rate of spread of a population across space). These two parameters are at the ecological heart of invasion biology. Recent advances in theoretical ecology have demonstrated that local population dynamics and spatial dynamics are often sensitive to different factors (Neubert and Caswell 2000). Therefore, determining the appropriate scale for a study of invasion may be vital for understanding the long-term fate of a population across a landscape, which in turn will affect our ability to apply science to its management.

Both spatial and temporal scaling issues affect control and restoration research and practice. At small plot scales, traditional weed scientists and herbicide applicators can predict the weed-killing efficacy and selectivity of various control methods with a high degree of certainty. Yet, because small plot studies often lack the spatial heterogeneity of large landscapes and are often short-term, the response of large sites to control, particularly over multiple years, is less predictable. In the case of removal experiments, adding more managed and unmanaged plots over a larger area would seem like a good idea from the perspective of experimental design. However, sprinkling unmanaged plots (ie plots full of invasive species) throughout a restoration/management area for an extended period of time is a protocol that could interfere with management goals (Horvitz and Koop 2001). It is also difficult to predict the ecological resilience of treated sites or the likely community response to interventions without knowledge of the specific context and the long-term responses of the particular community to perturbations. Long-term ecological studies, particularly over multiple sites, are therefore crucial, although managers faced with rapidly expanding plant invasions would be ill-advised to withhold control while awaiting the outcome of more extensive studies.

Small-scale, short-term data can be used to gain insight into large-scale, long-term processes through models. The key here is to design the sampling protocol to capture the expected heterogeneity and then apply models to gain insight into longer-term and larger-scale change. Long term experiments at large scales are the ideal source of data, but this is often not logistically feasible.

■ Integrated vegetation management as a guiding paradigm

McEvoy and Coombs (1999), in describing ecological approaches to weed control, formalized the terms "top-down" and "bottom-up" control, referring to kill techniques versus restoration of background vegetation and manipulation of processes affecting plant growth and reinvasion. Taken together with the prevention of

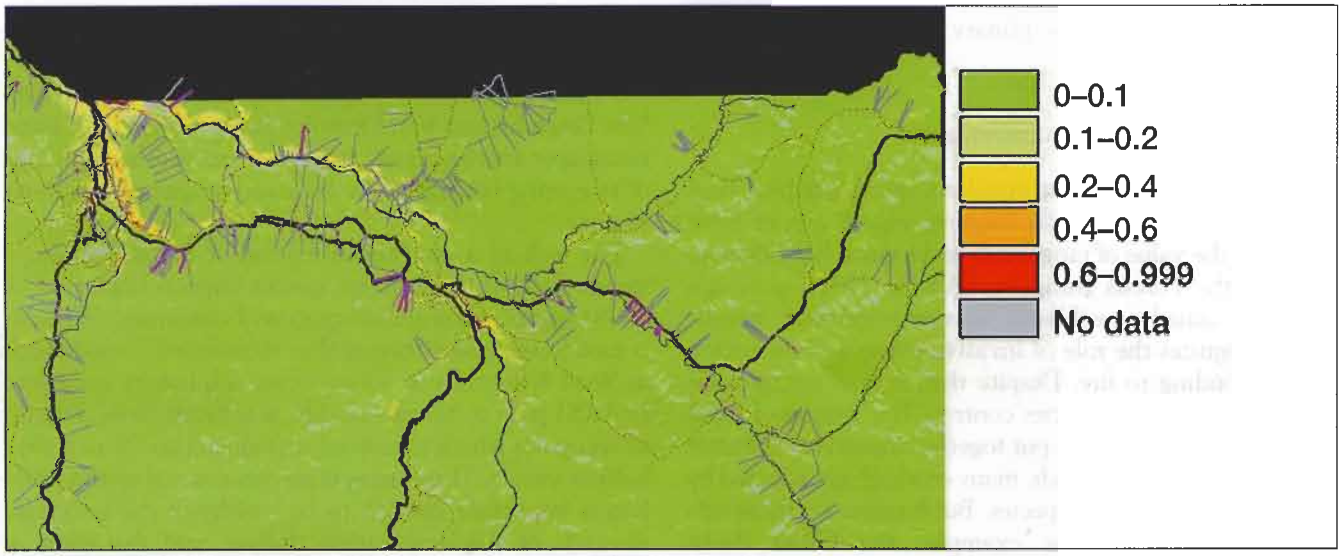

Figure 6. *A GIS-based probability of occurrence map for* Linaria dalmatica *(dalmation toadflax) in the northern range of Yellowstone National Park. Grey lines indicate actual transect locations where no toadflax was found in field surveys. Pink lines indicate transects where toadflax was present in field surveys. Numbers on right (and corresponding colors) indicate probability of occurrence of toadflax based on GIS rule set. Probability maps were generated by B Maxwell, R Aspinall, and L Rew, based on a large number of environmental variables as well as distance to roads and trails and current distribution, to assist managers in prioritizing sites for future monitoring for invasive species.*

propagule pressure, these constitute the basis for integrated weed management with a goal of sustainable land management. Despite appeals from ecologists and agency scientists for the implementation of such methods (McEvoy and Coombs 1999; Sheley and Krueger-Mangold 2003), this approach is still rare, as it is often too expensive, is not part of the mind-set of decision makers, or there is not enough scientific knowledge about a given system to be able to implement this type of program. Simply exerting top-down control denies the potential importance of disturbances, site condition, and land use in influencing site susceptibility to invasion. If the causes of plant community change are not addressed, then problems will persist (Sheley and Krueger-Mangold 2003) or new unwanted species will replace those removed (eg Alexander and D'Antonio 2003). Relative to the number of studies on how to kill weeds, very few published studies combine top-down with bottom-up control of weeds (eg McEvoy and Coombs 1999; Sheley *et al.* 2001; Wilson and Partel 2003) and even fewer use these principles to manage multiple weeds simultaneously. Yet to get beyond simply treating the symptoms, we must have more ecological, holistic approaches to vegetation management.

Research and management partnerships in the development of new tools

Scientific advancements, particularly in the area of spatial mapping and computer-based modeling, are increasingly being used to guide management of invasive species (Meyerson and Reaser 2003; Figure 6). However, there is uncertainty regarding the appropriate applications of such tools and their benefits relative to costs. Remote sensing (Despain *et al.* 2001; Koger *et al.* 2004) and analysis of aerial imagery could be used in early detection (eg used to detect *Lygodium* in tree islands in Florida; L Brandt pers comm), assessment of the scale of a potential problem, or for spatially based approaches to initiating control (Figure 6). To effectively develop these tools, partnerships are needed between skilled tool users, researchers, and managers.

The use of mathematical models such as matrix modeling of population dynamics has been suggested as an aid for controlling undesirable species by targeting points in the life history that might have the greatest effect on population growth, for targeting sites where control might be more feasible, and for evaluating the potential efficacy of a control agent. For example, it has been suggested that it would be a mistake for managers to assume that a biocontrol agent that was effective in the US would also work in New Zealand, because effectiveness is limited by how sensitive population dynamics of the targets are to seed production (K Shea pers comm; Shea and Kelly 1998), which differs between the continents. Sensitivity structure often varies widely among populations, and models might help to make variability in vulnerable life stages more apparent.

It is not reasonable to expect managers of natural areas to become mathematicians or experimental design or remote-sensing experts. Since invasive species can present an acute threat to the viability of natural areas as repositories of local biodiversity, or as providers of ecosystem services, there is a great need for collaboration between empiricists, modelers, and managers. The challenge is to create a culture in which building long-term interactions and interdisciplinary teams is the norm (A Bartuska pers comm).

■ Meeting the funding challenges

It is clear from the recent mandates of most federal land management agencies that invasive exotic species have degraded the value of rangelands and forests. For example, the Healthy Forests Initiative (August 2002), although primarily aimed at wildland fuels management, specifically recognizes the role of invasive plants in influencing and responding to fire. Despite this, it does not provide funding for invasive species control. The Bureau of Land Management (BLM) has put together initiatives to better manage their western lands, many of which are covered by undesirable non-native species. But funding for these initiatives is limited. For example, the Great Basin Restoration Initiative (GBRI) outlines a series of potential approaches to restoring rangelands heavily invaded by weeds; externally funded research projects in the region will help provide a scientific basis for meeting the goals of the GBRI, but implementation funds are insufficient. Involvement of economists with biologists and managers would help to evaluate the benefits and costs of management alternatives.

In other cases, parks and reserves lack sufficient funding to even put together weed management plans. For example, as recently as 2003, Yosemite National Park did not have a weed management plan because limited funding restricted personnel availability (L Ordonez pers comm). Because much of the research relevant to land management is being done by university-affiliated researchers with external funding, science can move at a faster pace than management which is tied to limited annual budgets. With respect to Yosemite, scientists from the University of California-Davis have modeled habitats within the park that are most likely to be invaded by ecologically damaging plants, providing Park staff with information on where to focus early detection and eradication efforts (J Randall pers comm). Similarly, funding for invasive species control in Everglades National Park (ENP) is extremely limited and focuses on just a few species (T Pernas pers comm). Ironically, regional county parks have been more successful in obtaining funding for alien species control than has ENP. Because of proximity and habitat similarities, populations managed by one agency could be propagule sources for others. University researchers may have an important role to play in facilitating communication between different local agencies to seek funding for research that would provide a sound basis for future management actions.

■ Conclusions

Over the past two decades, basic and applied research have converged on the study of invasive species, their role in changing ecosystems, and approaches to their control and management. Public awareness has also improved due to an increased coverage of the problem by the mainstream press: popular books (eg Devine 1998; Van Driesche and Van Driesche 2000; Baskin 2002) and newspaper articles on the topic abound. Yet the challenge of managing lands affected by invasive species continues to grow.

The lack of a uniform definition of harm or a single metric with which to judge species impacts (Parker *et al.* 1999) impedes communication and consensus. While it is easy to recognize threats that introduced diseases such as West Nile virus or severe acute respiratory syndrome (SARS) pose to human health, it is much more difficult to recognize which plants are introduced and which alter habitat values. Thus, there is no consensus that the problem is important enough to be worthy of the necessary research or implementation dollars, and the effort it would take to initiate major policy reform. With respect to regulatory stagnation, Miller and Gunderson (2004) state: "The morass of human and social dimensions swirling around the issue of invasive species makes the lack of coherent and comprehensive laws easier to understand".

Greater clarification of the ecological threats posed by invasive plant species to valued ecosystem functions, and the benefits gained by controlling them, are essential steps if slowing the spread of these plants is to become reality. Research on invasion processes at all levels, from genetic changes during invasion to controls over demography and spread, is also essential to the formulation of science-based management.

A recurring theme is the need for partnerships between the research community and management. With pinched management budgets, researchers can potentially provide continuity for long-term monitoring, manpower for larger-scale experiments, quantitative analyses of past management actions, and access to new tools. Ecology and weed science have a primary role to play in helping managers to prioritize species for control, designing approaches to control, visualizing long-term outcomes, and understanding sources of variability in outcome, while managers have the difficult role of preserving threatened ecosystems and their values with limited data and scarce funds.

■ Acknowledgements

The authors would like to thank the many agencies and organizations that supported the IPINAMS/EMAPI conference in Ft Lauderdale, FL, and the many speakers who shared their knowledge and ideas. We thank L Hidinger, formerly of ESA, for her dedication to the success of the meeting. J Corbin, K Haubensak, and K Wilson provided feedback on an earlier draft. L Ordonez allowed us to quote her regarding Yosemite's weed management activities, J Levine helped track down the data for Figure 2, and B Maxwell provided Figure 6.

References

Alexander JM and D'Antonio CM. 2003. Control methods for the removal of French and Scotch broom tested in coastal California. *Ecol Restor* **21**: 191–98.

Baskin Y. 2002. A plague of rats and rubber vines. Covelo, CA: Island Press.

Daehler CC, Denslow JS, Ansari S, and Kuo H. 2004. A risk-assessment system for screening out harmful invasive pest plants from Hawaii and other Pacific Islands. *Conserv Biol* **18**: 1–9.

Despain DG, Weaver T, and Aspinall RJ. 2001. A rule-based model for mapping potential exotic plant distribution. *West N Am Naturalist* **61**: 428–33.

Devine RS. 1998. Alien invasion. America's battle with non-native plants and animals. Washington DC: National Geographic Society.

Elton C. 1958. The ecology of invasions by animals and plants. London, UK: Methuen.

Gaskin JF and Schaal BA. 2002. Hybrid *Tamarix* widespread in US invasion and undetected in native Asian range. *P Natl Acad Sci USA* **99**: 11256–59.

Hausman JA. (Ed). 1993. Contingent valuation: a critical assessment. In: Contributions to economic analysis, Vol 220. Amsterdam: North Holland Press.

Hill G and Greathead D. 2000. Economic evaluation of classical biological control. In: Perrings C, Williamson M, and Dalmazzone S (Eds). The economics of biological invasions. Cheltenham, UK: Edward Elgar Publishing.

Horvitz CC and Koop A. 2001. Removal of non-native vines and post-hurricane recruitment in tropical hardwood forests of Florida. *Biotropica* **33**: 268–81

Kennedy TA, Naeem S, Howe K, *et al.* 2002. Biodiversity as a barrier to ecological invasion. *Nature* **417**: 636–38.

Koger CH, Shaw DR, Reddy KN, and Burce LM. 2004. Detection of pitted morning glory (*Ipomaea lacunose*) with hyperspecral remote sensing. II. Effects of vegetation ground cover and reflectance properties. *Weed Sci* **52**: 230–35.

Leung B, Lodge DM, Finnoff D, *et al.* 2002. An ounce of prevention or a pound of cure: bioeconomic risk analysis of invasive species. *P Roy Soc Lond B* **269**: 2407–13.

Levine J and D'Antonio CM. 1999. Elton revisited: a review of the evidence linking diversity and invasibility. *Oikos* **87**: 1–12.

Levine JM. 2000. Species diversity and biological invasions: relating local process to community pattern. *Science* **288**: 852–54.

Lonsdale WM. 1999. Global patterns of plant invasions and the concept of invasibility. *Ecology* **80**: 1522–36.

McEvoy PB and Coombs EM. 1999. Biological control of plant invaders: regional patterns, field experiments, and structured population models. *Ecol Appl* **9**: 387–401.

Meyerson LA and Reaser JK. 2003. Bioinvasions, bioterrorism and biosecurity. *Front Ecol Environ* **1**: 307–14.

Miller ML. 2004. The paradox of US alien species law. In: Miller ML and Fabian RN (Eds). Harmful invasive species: legal responses. Washington, DC: Environmental Law Institute.

Miller ML and Gunderson LH. 2004. Biological and cultural camouflage: the challenges of seeing the harmful invasive species problem and doing something about it. In: Miller ML and Fabian RN (Eds). Harmful invasive species: legal responses. Washington DC: Environmental Law Institute.

Naeem S, Knops JM, Tilman D, *et al.* 2000. Plant neighborhood diversity increases resistance to invasion in experimental grassland plots. *Oikos* **91**: 97–108.

National Invasive Species Council. 2001. Meeting the invasive species challenge: national invasive species management plan. Washington DC: National Invasive Species Council.

Naylor RL. 2000. The economics of alien species invasions. In: Mooney HA and Hobbs RJ (Eds). Invasive species in a changing world. Covelo, CA: Island Press.

Neubert MG and Caswell H. 2000. Demography and dispersal: calculation and sensitivity analysis of invasion speed for structured population models. *Ecology* **81**: 1613–28.

Newsome AE and Noble IR. 1986. Ecological and physiological characteristics of invasive species. In: Groves RH and Burdon JJ (Eds). Ecology of biological invasions. Cambridge, UK: University Press.

NRC (National Research Council). 2002. Predicting invasions of nonindigenous plants and plant pests. Washington DC: National Academy Press.

Parker IM, Simberloff D, Lonsdale WM, *et al.* 1999. Impact: toward a framework for understanding the effects of invaders. *Biol Invasions* **1**: 3–19.

Pheloung, PC, Williams PA, and Halloy SR. 1999. A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *J Environ Manage* **57**: 239–51.

Reichard SH and Hamilton CW. 1997. Predicting invasions of woody plants introduced into the United States. *Conserv Biol* **11**: 193–203.

Rejmanek M. 1996. A theory of seed plant invasiveness: the first sketch. *Biol Conserv* **78**: 171–81.

Rejmanek M and Richardson D. 1996. What attributes make some plants more invasive? *Ecology* **77**: 1655–61.

Richardson DM, Pysek P, Rejmanek M, *et al.* 2000. Naturalization and invasion of alien plants: concepts and definitions. *Divers Distrib* **6**: 93–107.

Shea K and Kelly D. 1998. Estimating biocontrol agent impact with matrix models: *Carduus nutans* in New Zealand. *Ecol Appl* **8**: 824–32.

Sheley RL, Jacobs JS, and Lucas DE. 2001. Revegetating spotted knapweed infested rangeland in a single entry. *J Range Manage* **54**: 144–51.

Sheley RL and Krueger-Mangold J. 2003. Principles for restoring invasive plant-infested rangeland. *Weed Sci* **51**: 260–65.

Shogren JF. 2000. Risk reduction strategies against the "explosive invader." In: Perrings C, Williamson M, and Dalmazzone S (Eds). The economics of biological invasions. Cheltenham, UK: Edward Elgar Publishing.

Simberloff D. 2003a. Confronting introduced species: a form of xenophobia? *Biol Invasions* **5**: 179–92.

Simberloff D. 2003b. Eradication: preventing invasions at the outset. *Weed Sci* **51**: 247–53.

Stohlgren TJ, Binkley D, Chong D, *et al.* 1999. Exotic plant species invade hot spots of native plant diversity. *Ecol Monogr* **69**: 25–46.

Stohlgren TJ, Barnett DT, and Kartesz JT. 2003. The rich get richer: patterns of plant invasions in the United States. *Front Ecol Environ* **1**: 11–14.

Tilman D. 1997. Community invasibility, recruitment limitation, and grassland biodiversity. *Ecology* **78**: 81–92.

Turpie J and Heydenrych B. 2000. Economic consequences of alien infestation of the Cape Floral Kingdom's fynbos vegetation. In: Perrings C, Williamson M, and Dalmazzone S (Eds). The economics of biological invasions. Cheltenham, UK: Edward Elgar Publishing.

US Congress. 1993. Harmful non-indigenous species in the United States. Office of Technology Assessment OTA-F-565. Washington DC: US Government Printing Office.

USDA/FAS. 1999. The World Trade Organization and US Agriculture. US Department of Agriculture, Foreign Agricultural Service. http://www.fas.usda.gov/info/factsheets/wto.html. Viewed 16 November 1999.

Van Driesche J and Van Driesche R. 2000. Nature out of place. Covelo, CA: Island Press.

Wilson SD and Partel M. 2003. Extirpation or coexistence? Management of a persistent introduced grass in a prairie restoration. *Restor Ecol* **11**: 410–16.