Reprinted from: Issue Paper. Febraury 2000. 13:1-18.

Published by: Council for Agricultural Science and Technology. Ames, Iowa.

Invasive plant species[1]

BARBRA H. MULLIN[a] LARS W. J. ANDERSON[b], JOSEPH M. DITOMASO[c], ROBERT E. EPLEE[d], and KURT D. GETSINGER[e]

Authors are as follows: [a](Chair), Montana Department of Agriculture, Helena, Montana; [b]USDA-ARS, Exotic and Invasive Weed Research, University of California, Davis; [c]Department of Vegetable Crops, Weed Science Program, University of California, Davis; [d]USDA-APHIS, Whiteville, North Carolina; [e]U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Summary:

Invasive plant species are one of the greatest threats to croplands, rangelands, aquatic areas, and wildlands in the United States. They degrade the productivity and biological diversity of all ecosystems. W. M. Lonsdale (1994) noted "A mine that modified the landscape on a similar scale (to invasive plants) would be subjected to intense scrutiny by the environmental impact assessment process and would probably not be approved." The problem increases each year as new species are introduced and established. We can overcome and reverse this trend only if we are willing to commit and use national resources to combat the problem. The formula for success must include a coordinated effort at the federal, state, institutional, and private sector levels that will involve long-term commitments of adequate planning, funding, scientists, and facilities to produce results based on sound science. Programs based on arbitrary geopolitical boundaries must be replaced by approaches based on ecosystem-scale realities.

Increased and consistent funding to support public and industry educational programs, a centralized detection and reporting system, and expanded mitigation and research programs are critical to reducing the continued spread and current damage caused by invasive weed species. In addition, greater uniformity and consistency among state and federal regulatory and enforcement agencies, coordinated through an effective national plan, would reduce the potential for invasive weed introductions into the United States and between states into sensitive habitats throughout the nation.

[1]Reviewers: Douglas J. Doohan, Department of Horticulture and Crop Science, Ohio State University, Wooster; William T. Haller, Center for Invasive and Aquatic Plants, University of Florida, Gainesville; Robert H. Hedberg, Director of Science Policy, Weed Science Society of America, Washington, D.C.; Rodney G. Lym, Department of Plant Sciences, North Dakota State University, Fargo; John M. Randall, The Nature Conservancy, Wildland Weeds, Management and Research, Department of Vegetable Crops and Weed Sciences, University of California, Davis.

Introduction

Agriculture in the United States depends on a variety of native and non-native plant species; most U.S. crops are species, strains, varieties, and cultivars of non-native plants. In contrast, the stability and ecological function of natural wildlands depend on a diverse community of native plants. Throughout the last century, however, large numbers of extremely damaging plants have been introduced into and established in the United States (Table 1). These introductions range from accidental, such as weed seed contamination of commodities, to purposeful, such as purple loosestrife and other plant species introduced as ornamental plantings. Regardless of the mode of entry of these introductions, the public has suffered economic losses to food and fiber production, deterioration of natural resources (rangeland and wildlands, aquatic and riparian sites, and forests), loss of native species and their habitat, and further economic losses due to restrictions on the export of pest-contaminated commodities.

The risk of injurious introductions of undesirable plants has greatly accelerated in the last three decades due to exponential increases in air-travel, increased ports of entry, expanded export/import to international markets, and increased access to foreign ecosystems. Through commercial air-cargo, ship ballast water, and private travel, hundreds to thousands of non-native plant species are brought into the United States each year (Cohen and Carlton, 1998). Though most of these species have not survived or established in the United States, enough have to cause a continued threat to an already pest-burdened crop-production system and to our sensitive and dwindling natural resources. Examples include millions of acres of leafy spurge and spotted knapweed on western rangelands; the parasitic plant witchweed, which threatens important agronomic crops across the southern United States; and the recent invasion of giant salvinia, which poses a severe ecological and economic threat to the lower Colorado River system.

The President's Executive Order on Invasive Species (Clinton, 1999) defines an invasive species as "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health." Although there are some federal regulatory constraints on movement, sale, and possession of exotic organisms, the overall resources directed at prevention, intervention, quarantine, removal, public awareness, and the enforcement of existing federal statues are seriously inadequate. Many states also have regulations governing invasive plant species but these regulations are inconsistent from state to state, may be confusing or contradictory, and do not adequately address the scope of the problem.

The economic impact of many weeds is poorly documented because of the difficulty in assessing impacts to habitats, such as forests, hay and pasturelands, rangelands, wildlands, aquatic, wetland, and riparian sites. Most documented impacts are from croplands, where a conservative estimate of the impact of weeds to agriculture is $20 billion each year (Bridges, 1994).

This paper was developed to give a clear overview of some of the most economically damaging invasive plants in rangeland, wildland, aquatic, riparian, and cropland ecosystems. Strengths and weaknesses of current weed programs are presented with suggested recommendations that will enhance our ability to slow new plant invasions and mitigate expansion and damage caused by established invasive plant species.

Table 1. Partial list of major economically and ecologically important invasive weed species In the United States

Habitat	Scientific name	Common name	Distribution
Riparian	*Ailanthus altissima*	tree-of-heaven	Widespread throughout U.S.
	Albizia julibrissin	mimosa	Expanding range in tropical regions, southeastern U.S.
	Arundo donax	giant reed	Expanding range in Pacific Coast states, Arizona
	Casuarina equisetifolia	Australian pine	Expanding range in Hawaii and Florida
	Delairea odorata	Cape ivy	Expanding range in California
	Elaeagnus angustifolia	Russian olive	Sporadic infestations throughout most of U.S.
	Lepidium latifolium	perennial pepperweed	Rapidly expanding range in West
	Phragmites communis	common reed	Widespread in eastern U.S., native to West
	Sapiem sebiferum	Chinese tallow	Carolinas to Florida, Texas, and central California
	Tamarix spp.	tamarisk, saltcedar	Rapidly expanding range in West
Aquatic or Wetlands	*Alternanthera philoxeroides*	alligatorweed	Widespread in southeastern U.S., some infestations in California
	Egeria densa	Brazilian elodea	West of the Mississippi River; some in California and southeastern U.S.
	Eichhornia crassipes	water hyacinth	Widespread throughout southeastern U.S. and California
	Hydrilla verticillata	hydrilla	Widespread in Southeast and mid-Atlantic coast to Connecticut, threatens western states
	Lythrum salicaria	purple loosestrife	Widespread in northern and central states, expanding range in West
	Melaleuca quinquenervia	melaleuca	Widespread in Florida
	Myriophyllum aquaticum	parrotfeather	Widespread throughout U.S.
	Myriophyllum spicatum,	Eurasian watermilfoil	Widespread throughout U.S.
	Salvinia molesta	giant salvinia	Well-established in Texas, new. infestations in California and other western and southeastern states
	Spartina alterniflora	smooth cordgrass	Native in estuaries of eastern U.S., spreading along coast of Pacific Northwest
	Trapa natans	water chestnut	Expanding range in northeastern U.S.
Rangeland and Wildland	*Acacia auriculiformis*	ear leaf acacia	Expanding range in Southeast
	Acroptilon repens	Russian knapweed	Widespread throughout U.S., particularly western states
	Aegilops spp.	goat grasses	Widespread in western U.S.
	Ammophila arenaria	European beachgrass	Isolated infestations along sand dunes of California
	Andropogon virginianum	broom sedge	Hawaii (native to southeastern U.S.)

Bromus madritensis ssp. rubens	red brome	Widespread in western states, especially Mojave and Sonoran deserts
Bromus tectorum	downy brome	Widespread throughout U.S., particularly western states
Cardaria draba	hoary cress	Widespread in western U.S.
Carduus nutans	musk thistle	Widespread throughout U.S.
Carpobrotus edulis	iceplant, sea fig	Spreading in coastal areas of West
Centaurea calcitrapa	purple starthistle	Expanding range in California
Centaurea diffusa	diffuse knapweed	Widespread in western U.S.
Centaurea maculosa	spotted knapweed	Widespread throughout U.S., particularly western states
Centaurea solstitialis	yellow starthistle	Western states, particularly California, Idaho, Oregon
Centaurea squarrosa	squarrose knapweed	Expanding range in western U.S.
Chondrilla juncea	rush skeletonweed	Expanding range in western U.S.
Cirsium arvense	Canada thistle	Widespread throughout U.S.
Cirsium vulgare	bull thistle	Widespread throughout U.S.
Conium maculatum	poison hemlock	Widespread throughout U.S.
Convolvulus arvensis	field bindweed	Widespread throughout U.S.
Cortaderia jubata	jubatagrass	Widespread along California and Oregon coast
Cortaderia selloana	pampasgrass	Widespread along California and Oregon coast
Crupina vulgaris	common crupina	Expanding range in California and northwestern states
Cynara cardunculus	artichoke thistle	Expanding range in California
Cynoglossum officinale	houndstongue	Expanding range in many regions of U.S.
Cytisus scoparius	Scotch broom	Widespread throughout Pacific Coast states
Ehrharta spp.	Veldtgrass	Expanding range in coastal areas of California
Euphorbia esula	leafy spurge	Widespread in northern states, particularly western U.S.
Funicular vulgare	fennel	Widespread throughout Pacific Coast states, especially southern California
Genista monspessulana	French broom	Widespread in western U.S.
Hedychium gardnerianum	Kahili ginger	Hawaii
Hieracium aurantiacum	orange hawkweed	Expanding range in Northwest
Hieracium pratense	meadow hawkweed	Expanding range in Northwest
Hypericum perforatum	St. Johnswort	Widespread in western U.S.
Imperata cylindrica	cogon grass	Expanding range in tropical and sub- tropical areas of U.S., southeastern U.S. to Texas and southern California
Isatis tinctoria	Dyer's woad	Spreading in Utah, California, and other western states
Lantana camara	lantana	Expanding range in Florida and Hawaii
Lepidium latifolium	perennial pepperweed	Rapidly expanding range in West

	Leucanthemum vulgare	oxeye daisy	Widespread throughout U.S.
	Linaria dalmatica	Dalmatian toadflax	Expanding range in West
	Linaria vulgaris	yellow toadflax	Expanding range in West
	Lonicera japonica	Japanese honeysuckle	Eastern and central U.S. and Hawaii
	Melia azedarach	Chinaberry tree	Spreading in Southeast
	Miconia calvescens	Miconia	Hawaii
	Myrica faya	firebush	Hawaii
	Onopordum acanthium	Scotch thistle	Widespread throughout West
	Passiflora mollissima	banana poka	Hawaii
	Polygonum perfoliatum	mile-a-minute	Expanding range in East
	Potentilla recta	sulfur cinquefoil	Widespread in northern states
	Psidium calleianum	strawberry guava	Hawaii
	Pueraria lobata	kudzu	Widespread in Southeast to Pennsylvania and Illinois
	Rubus argotus	Florida prickly blackberry	Hawaii (native to southeastern U.S.)
	Salsola tragus (= S. kali)	Russian thistle (tumbleweed)	Widespread in West
	Salvia aethiopis	Mediterranean sage	Expanding range in western U.S.
	Schinus terebinthifolius	Brazilian pepper	Expanding range in southwestern U.S.
	Senecio jacobaea	tansy ragwort	Widespread in Pacific Northwest
	Solanum viarum	tropical soda apple	Spreading in southeastern U.S.
	Spartium junceum	Spanish broom	Spreading in western states
	Taeniatherum caput-medusae	medusahead	Widespread in West
Cropland[1]	*Ulex europaeus*	gorse	Isolated infestations on Pacific Coast
	Abutilon theophrasti	velvetleaf	Widespread throughout much of U.S.
	Amaranthus retroflexus	redroot pigweed	Widespread throughout U.S.
	Aegilops cylindrica	jointed goatgrass	Widespread throughout U.S.
	Chenopodium album	common lambsquarters	Widespread throughout U.S.
	Cirsium arvense	Canada thistle	Widespread throughout U.S.
	Convolvulus arvensis	field bindweed	Widespread throughout U.S.
	Cyperus esculentus	yellow nutsedge	Widespread throughout U.S.
	Cyperus rotundus	purple nutsedge	Widespread throughout U.S.
	Echinochloa crus-galli	barnyardgrass	Widespread throughout U.S.
	Elytrigia repens	quackgrass	Widespread throughout U.S.
	Kochia scoparia	kochia	Primarily invasive in western U.S.
	Setaria spp.	foxtails	Widespread throughout U.S.
	Sorghum halapense	Johnsongrass	Widespread throughout U.S.
	Striga asiatica	witchweed	Eradicated or close to eradication in North and South Carolina

Strengths and weaknesses of current invasive plant programs

Prevention programs

A step-by-step approach to protecting ecosystems from invasive plant species should include (1) predicting which species are likely to enter the United States and successfully erecting barriers (regulation, inspection, quarantine, destruction) to prevent entry of those species; (2) implementing specific site management and control measures to prevent establishment and spread from sites of initial introduction; and (3) developing management zones in sites of establishment to initiate control and prevent spread to new areas. Prevention of the introduction of known pests and the establishment of newly introduced invasive plant species are economical and rational approaches to stopping the spread of invaders before they become economically damaging to the environment.

Preventing introduction of invasive plant pests into the United States depends on awareness and action along a chain of transport that includes (1) a permitting system to bring plants into the United States; (2) point of entry inspections at airports, state borders, and post offices; (3) point-of-sale permitting and education for retailers; and (4) point-of-use education for home, industrial, aquatic, and terrestrial landscape managers and hobbyists. Because many invasive plants are not restricted under the Federal Noxious Weed Act, the current permitting system is inadequate to stop entry of species that have been identified as detrimental and are currently sold and distributed in the United States. Inspections have been most effective in stopping a few highly regulated species such as hydrilla, but increased volume of air traffic and shipments has overwhelmed present border inspection capacities.

Wholesalers and retailers often are not knowledgeable enough to distinguish between native and exotic species. There is no adequate educational program to ensure that retailers are fully aware of import restrictions, that allow for proper identification of plants, nor provide information on where to report suspect species. The user-end knowledge base and awareness levels of invasive plants are limited. Many restoration managers and landscape architects are aware of problem species; however, the average property owner is poorly informed. The historical record clearly demonstrates that the widespread introduction, distribution, and, in some cases, promotion of many environmentally costly exotic plants were made by state and federal agencies or by well-intentioned commercial growers and suppliers. Prevention programs for invasive plant species must include enforcement and controls coupled with adequate education throughout the entire sequence of importation.

Public education and awareness programs

Awareness of invasive plant species and the problems they cause will help the general public, policy and lawmakers, administrators, and land managers understand why the development of long-term weed management programs is critical to protect the environment. Communicating the impacts of invasive plant species, their correct identification,

and the management tools available to land managers will aid in development of management plans at all levels of ownership - local, state, and federal.

Educational efforts are being made through academia, industry, commodity groups, and farm and nonprofit organizations to enhance awareness of the threats associated with invasive weeds as biological pollutants and the methods of dispersal of pest plants as contaminants of agricultural and horticultural commodities. These educational efforts can be accomplished by a number of methods: through brochures, posters, internet websites, calendars, scientific papers, and other written media; with educational programs for landowners, land managers, or the general public that include public seminars, professional symposia, school programs, and volunteer field workshops; and by using the media to educate the public through radio or television news stories, public service announcements, and newspaper. Educational activities will facilitate greater cooperation between private, federal, state, and county agencies, industries, landowners, and the general public and increase the likelihood of early detection and rapid response to new infestations.

Recent educational efforts that have greatly improved public awareness of noxious and invasive weeds can be found across the United States. For example, excellent printed materials and roadside billboards educating the public about invasives such as spotted knapweed in Montana, hydrilla in California, and Eurasian watermilfoil in Minnesota have been developed. Unfortunately, for most exotic species, the level of awareness by the general public is low. Educational efforts for invasive rangeland, wildland, and cropland weeds have been directed mainly at rural populations. Impacts of invasive weeds on the environment need to be the focus of educational programs in urban areas and within the nursery industry. Short and effective public service announcements directed at larger urban centers and targeted to those groups and individuals that provide plants or promote their use in ornamental and aquatic settings should be developed.

Early detection, monitoring, and reporting programs

Early detection means locating, identifying, and documenting newly introduced species. This is essential to reduce the long-term economic impact of new invading species. It is critical that early identification and monitoring be accurate and timely. Detected invaders must be identified and reported to an appropriate organization to allow for initiation of assessment and response. Centralized monitoring programs could pool all available information on an invasive plant species and help in evaluating the success or failure of weed management programs. Reporting requirements allow all available information on invasive plant species to be documented and shared with land managers.

The best management of invasive weeds is to recognize potential weed problems early, control them before they reproduce and spread, and monitor the site regularly to maintain adequate follow-up control. Early detection depends on proper training of land managers, pest management professionals, and property owners. Understanding the potential threats that may exist on surrounding property and in aquatic systems can provide motivation for the public to provide an early warning system for weed invasion. Among invasive weed species, the hydrilla program is the most visible and organized. In California, the hydrilla program consists of interdiction at state borders and ports of entry and field monitoring to detect new sites and to assess the effectiveness of eradication efforts

in previously identified hydrilla infestations. The success of this approach relies on coordination between the California Department of Food and Agriculture (CDFA) and regulatory agencies. The County Extension offices serve as early detection centers for the public and water managers. More recently, alerts regarding giant salvinia have been useful in discovering new or existing infestations. Unfortunately, staffing, training, and funding limitations typically prevent adequate surveillance for most invasive weeds.

The cost of eradication or management years later is considerably more expensive than the initial cost of eliminating a population following early detection (Figure 1). Leafy spurge was detected in Montana in the 1930s and early extension reports indicated the seriousness of this plant and the need to control infestations. Adequate controls were not available and awareness of the potential impacts were not clearly understood. A cohesive program was not designed at that time and Montana now combats more than 600,000 acres of leafy spurge and suffers an annual $2.2 million loss of grazing capacity (Bangsund and Leistritz, 1991).

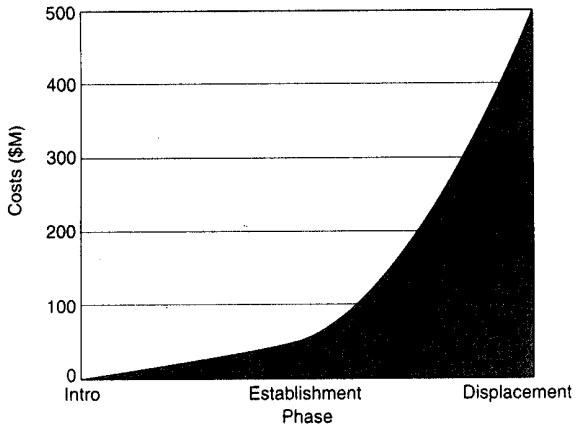

Figure 1. Management costs in million dollars and invasion phase relationship show that prevention is the least costly phase, with exponentially rising costs once the invading weed has become established and most costly if it is displacing native species and/or disrupting native habitats (Anderson, 2000).

Rapid response to new infestations is also hampered by the lack of a central, well-known, and easily accessible center for reporting. Thus, there are often significant delays between detection and response to new infestations. A much broader and coordinated communication network is needed to ensure interstate communications to enable early and effective response. One possibility is to establish a national, accessible reporting system such as a "Pest Alert" number.

Mitigation and control programs

Mitigation and control of invasive plant species is accomplished by the development and implementation of a long-term management plan that integrates knowledge of plant biology and site requirements. Integrated weed management (IWM) programs are built on an understanding of the biology of the weed species and the infested ecosystem and on the use of the most effective control techniques available for the weed species and site. Best management techniques available for the target weed are employed in a planned, coordinated program to limit the impact and spread of the invasive plant. Control methods are determined by the use objectives for the land, the effectiveness of the control method on the target plant, environmental factors, economics, policy and legal restric-

tions, and the extent and nature of the infestation. Common components of IWM programs include herbicides; cultural control methods, including grazing management, fertility management, prescribed burnings, and revegetation programs; physical and mechanical methods, including mowing, tillage, and pulling; and biological control, including the use of host-specific insects and plant pathogens.

Mitigation programs, especially in rangeland, wildland, aquatic, and riparian sites, are expensive and require a considerable knowledge of the ecosystem and environmental conditions. Most mitigation programs are directly associated with a particular weed species and a specific management program. Most IWM programs are local in scale, rather than regional or area-wide. For some sites, this small-scale approach is acceptable due to the unique nature of the specific location and habitat. However, area-wide cooperative management programs are much more effective, in both management and cost, than individual programs with no planned coordination. Larger scale programs on squarrose knapweed in Utah; leafy spurge in Montana, Wyoming, North Dakota and South Dakota; and the Eurasian watermilfoil project in the Panhandle of Idaho illustrate the success of regional invasive plant programs. At a minimum, regional programs based on similar ecosystem management goals should be encouraged across the United States. These programs could form the basis for sustainable wildlife habitats and, in the long run, help reduce susceptibility to exotic invasive plants. Little work has been conducted with control programs for noxious weeds in wildland areas. Lack of funding for research has hampered these efforts.

Managing invasive plant species requires a clear understanding of the land use objectives and beneficial vegetation needed to accomplish established management goals. Programs that concentrate on the control of the weed, with no plan for development of beneficial species in the area, are often unsuccessful. Much more effort must be directed at establishment and encouragement of native, beneficial plants or high quality perennial grasses. In many cases, resident native vegetation is adequate to replace the invasive species. In Florida, melaluca control programs allow natural reestablishment with sawgrass and other vegetation. Revegetation may not be practical or needed in many aquatic sites. However, some projects need a specific revegetation plan and effort to restore the native or beneficial vegetation in infested areas. Often, funding limitations prohibit these integrated efforts. There are some revegetation efforts underway in areas of northern California along riparian and irrigation systems and in wildlife refuges and in Montana rangelands heavily infested with spotted knapweed. However, there are currently no consistent programs or sources for native and other beneficial plants used in these revegetation efforts, nor funding for actual planting.

Judicious and selective use of herbicides is an important tool in any IWM program. Herbicide use may be limited in aquatic, riparian, rangeland, and wildland sites due to site-use restrictions, lack of efficacy on the target species, lack of research on the target species, cost factors, or public opposition to the use of herbicides in many of these areas. The cost of development for herbicides limits the target weeds and control situations where agricultural chemical companies are willing to invest research funding. Additional public research into new herbicide uses, herbicide use rates, and targeted application techniques would benefit the IWM approach, especially when economics do not attract private sector research. The USDA-Cooperative State Research, Education, and Exten-

sion Service IR-4 program funds herbicide research on minor use crops. This process should be expanded to include herbicide use in rangelands and wildlands as well.

Site restrictions often limit the use of many physical and mechanical methods of control, but, again, funds are limited for development of appropriate and creative integrated approaches for the management of invasive species.

Biological control agents, if available, can be effective components of an IWM approach. All invasive species are candidates for the development of a biological control program. Some species are so closely related to economically important crops, however, that classical biological control agents may not be available. Selective biological control agents have not been developed for all weed species and may not be appropriate for all weed species. For example, tropical soda apple is closely related to tomatoes, peppers, eggplant, and other valuable crops and may not be a good candidate for a biological control research program. Careful assessment of the risks and benefits for biological control for a weed species should be taken prior to the initiation of a research program.

The most successful research, development, and implementation programs for biocontrol agents have been through cooperative efforts of federal and state researchers and agencies with support from county and local entities. Biological control agents must go through rigorous host specific testing prior to introduction into the country to prevent the accidental introduction of a serious crop pest. Currently, the development of effective biological control agents is limited by federal regulations that classify biocontrol agents as plant pests, the lack of a coordinated program at the national level, and the lack of consistent funding. Several promising biocontrol agents recommended for approval by the USDA's Animal and Plant Health Inspection Service Technical Advisory Group (APHIS-TAG) based on scientific data have been stopped in the final stages of the approval process. Objections for release are often from U.S. Fish and Wildlife Service (FWS) representatives who have not been involved in the review process early and do not clearly understand the research and review on which TAG bases its recommendation. TAG includes representation from FWS and the research and approval process is clearly outlined in APHIS policy. The FWS and other agency representatives on TAG must involve their concerned personnel early in the approval process.

Research programs

Resources and scientific expertise dedicated to economically important elements of plant sciences have been historically funded at levels that have allowed the United States to achieve great advances in the field of weed science in cropland settings, leading to unprecedented production of food and fiber. However, funding and the number of experienced researchers focused on understanding the biology, ecology, and sustainable management strategies of invasive exotic weeds and their inherent impact are extremely limited. Rangeland and wildland research programs are limited to the western and southern states. Funding for these programs has declined by as much as 50% during the past decade, in spite of increased demands for solutions to problems created by invasive plants. Current research programs in riparian and aquatic areas include the few laboratories devoted to management of aquatic vegetation supported by either state or federal funding, including federal facilities in Florida, California, Colorado, and Mississippi and

a state facility in Florida. This realignment of scientific expertise has caused a proportional shift away from applied to more fundamental research, simply because federal and state agencies are receiving smaller allocations for research and development efforts. Although some academic researchers are conducting studies on many invasive plant species, new management technologies that could be implemented on a regional or national level are not being developed due to a lack of central coordination, low funding levels, and limited resources provided by government agencies.

In many cases, little is known about the biology, life history, and appropriate control methods of an exotic invader, particularly with respect to its newly acquired habitat. Well-funded and consistent research programs are critical to success in managing established and newly invading plant species. Successful research requires highly trained individuals and specialized facilities that must be supported and maintained for extended periods. Fluctuating budgets and their subsequent effect on personnel training, turnover, and continuity of effort must be avoided.

An ecologically based approach to managing invasive plant species should be expanded to aggressively engage recently introduced species that are expanding at exponential rates. Because invasive plants are not restricted by political boundaries in their growth and pattern of infestation, the federal government must provide a leadership role in rebuilding and maintaining viable research programs that can use resources from local governments, academia, and the private sector. Research and development activities must be coordinated within states, regions, and the nation to foster regular communication among investigators, prevent unnecessary duplication of research efforts, and target research funding. It will take a national research program based on sound science in ecology, combined with the rapid development and use of environmentally compatible herbicide technology and biological control, to stem the invasive tide of exotic plants that threaten the ecological integrity of aquatic, riparian, rangeland, wildland, and cropland ecosystems in the United States.

Legislation and regulations

Invasive plant species are regulated at all levels of government. Local regulations often include control of invasive plants by county weed districts or a similar entity. Some states have specific control responsibilities, while others have prevention programs in place, such as seed, feed, and quarantine laws. At the national level, federal land managers have the responsibility to develop weed management programs on their lands in states with active weed programs and laws. The USDA Animal and Plant Health Inspection Service has the responsibility of preventing the movement of undesirable plant species into the United States and enforcement of the Federal Noxious Weed Act.

Effective laws, regulations, and policies are fundamental to preventing invasive pest plants from being introduced into, becoming established in, and persisting at sites where they cause economic loss or environmental damage. Laws across the jurisdictions of local, county, and state entities must meet the needs of the local citizens and complement regulations at the national level. Any system must include an infrastructure that ensures compliance through an informed public and appropriate civil penalties. In addition, information must be readily available to all levels of government on what plants are con-

sidered pests, how and where they can or cannot be moved, and other information to facilitate compliance. State weed laws should be designed to protect their lands and citizens, with complementary federal laws to protect the nation's borders and support state management programs. The federal laws and regulations related to the movement of invasive plants are not adequate to ensure the protection of non-infested areas. There is no central database system that provides a complete listing of the invasiveness category of plants that move as commodities or as contaminants. Nor is there a national source to inform the public of the federal and state regulatory action category for individual weeds. Without a system to provide the public with information on invasiveness, there cannot be effective restriction in the movement of invasive plants.

With the exception of quarantines and border inspections at points of entry for hydrilla in California, Washington, and Florida, most states have limited statutory authority to deal with invasive, plants. A voluntary regional program certifies weed-free hay movement between several western states. Some state quarantine laws limit movement of commodities that are not inspected or certified, but there is little consistency between states and enforcement is difficult due to lack of staff and funding. Lack of funding for enforcement also limits the effectiveness of the Federal Noxious Weed Act in stopping transport, sale, and dispersal of exotic invasive weeds. Personnel to monitor and inspect potential points of sale and distribution are inadequate. This deficiency is illustrated by the recent offering for sale of giant salvinia, an aquatic species on the Federal Noxious Weed List, in more than sixty cities in California through wide-scale advertising on web sites. Either due to lack of knowledge of the existing federal laws, or flagrant disregard for these laws, exotic weeds are being offered for sale to the public by electronic, local retail, and magazine and mail order sources. Both state and federal regulations need adequate enforcement support.

In addition, a more streamlined process is urgently needed for including new noxious weeds in existing regulatory restrictions. Any improvement in these processes also will require much more focused education programs aimed at the trades and hobbyists that form the largest network for importation of exotic species. The goal should be strong incentives to comply based on sound environmental stewardship practices backed up by appropriate regulatory authority and penalties when laws are broken. Most importantly, there is a critical need for a strong federal program and for uniformity and consistency between the various states' regulatory and enforcement approaches. This regulatory consistency is essential to maximize the abilities of each–state and the United States–to keep out invading species; it is the only rational way to ensure equity in the market place and the trades related to invasive plants.

Federal land management agencies are required by Section 2814 of the Federal Noxious Weed Act to (1) designate an office or person adequately trained in the management of undesirable plants to develop and coordinate a management program for all weeds on lands under the agency's jurisdiction; (2) establish and adequately fund a weed management program; (3) complete and implement cooperative agreements with state agencies regarding the management of weeds; and (4) establish integrated systems to control or contain weeds targeted under cooperative agreements. Federal land management agencies lack funding and staff to implement this section of the Federal Noxious Weed Act, but it

is the section that is in most need of funding at a level that will combat invasive plants at the point of invasion.

Many states have a weed law and state listed noxious weeds. These laws are designed to best complement the needs of that state and its residents. States that do not currently have a weed law or a state noxious weed list must be encouraged to develop a workable plan that is consistent with surrounding states and federal land management goals.

Recommendations

Develop coordinated prevention programs

- Identify potentially invasive species from foreign lands that must not be introduced into the United States and support more thorough border inspections.
- Provide accountability throughout transport using a permit system that identifies potential invasive plants and prevents sales of invasive and noxious species.
- Ensure that wholesalers and retailers are fully aware of import restrictions, proper identification of plants, and where to report suspect invasive species.
- Require all projects promoting non-native species for forage, revegetation, erosion control, and similar projects to screen species and cultivars for invasiveness prior to use.
- Include enforcement and controls, coupled with adequate education, from importation to the end-user.
- Adequately document the impacts of invasive plant species on the economics and environment of the United States.

Increase education and public awareness

- Expand media coverage and target social awareness of the threat of invasive weeds as biological pollutants in the urban sector through a national Invasive Species Environmental Stewardship program.
- Improve educational programs within the nursery industry and among users of areas threatened by invasive plants and provide funding for increased support of educational programs, including a comprehensive K-12 education curriculum.
- Improve detection and reporting systems by developing an easily recognized central rapid response center for reporting new invasive weed populations.

Develop coordinated mitigation and control programs

- Use the most effective current state programs as models to encourage regional and national programs.
- Develop and implement additional integrated approaches to management, including chemical control methods that are consistent across political boundaries and can be implemented regionally.

- Develop restoration programs that encourage the use of beneficial species in areas of infestation.
- Develop consistent regional and area-wide management programs that encourage cooperation of all land managers and landowners and include a "strike force" operation to stop incipient infestations.
- Encourage a national program of coordination in the development and implementation of biological control.

Increase research on the biology, ecology, and control of invasive plants

- Identify current centers of excellence and develop coordinated research agendas on a regional and national scale.
- Maintain specialized research and development facilities, as well as trained and experienced scientists and staff.
- Expand research and development efforts in ecologically based integrated weed management, which includes selective use of herbicides, cultural practices, mechanical means, and weed-specific biocontrol agents. Provide national and regional guidance and coordination of relevant research and development efforts among scientists and agencies/institutions.

Improve and harmonize current laws and regulations at all levels

- Use existing effective state laws as models.
- Develop a central database that provides information on state and federal regulatory actions for all invasive species.
- Improve the federal Noxious Weed Act, making the listing process faster and allowing agencies to stop interstate transport of federal noxious weeds, and strengthen enforcement.
- Support uniformity and consistency among all local, state, and federal authorities.
- Encourage states without state weed laws to develop and implement laws that are consistent with laws in other states.

Case histories: Invasive plant species in certain ecosystems

Rangeland and wildland ecosystems

Rangeland and wildlands comprise over 50% of the total land area of the United States. These lands provide valuable resources to wildlife and are areas of recreational

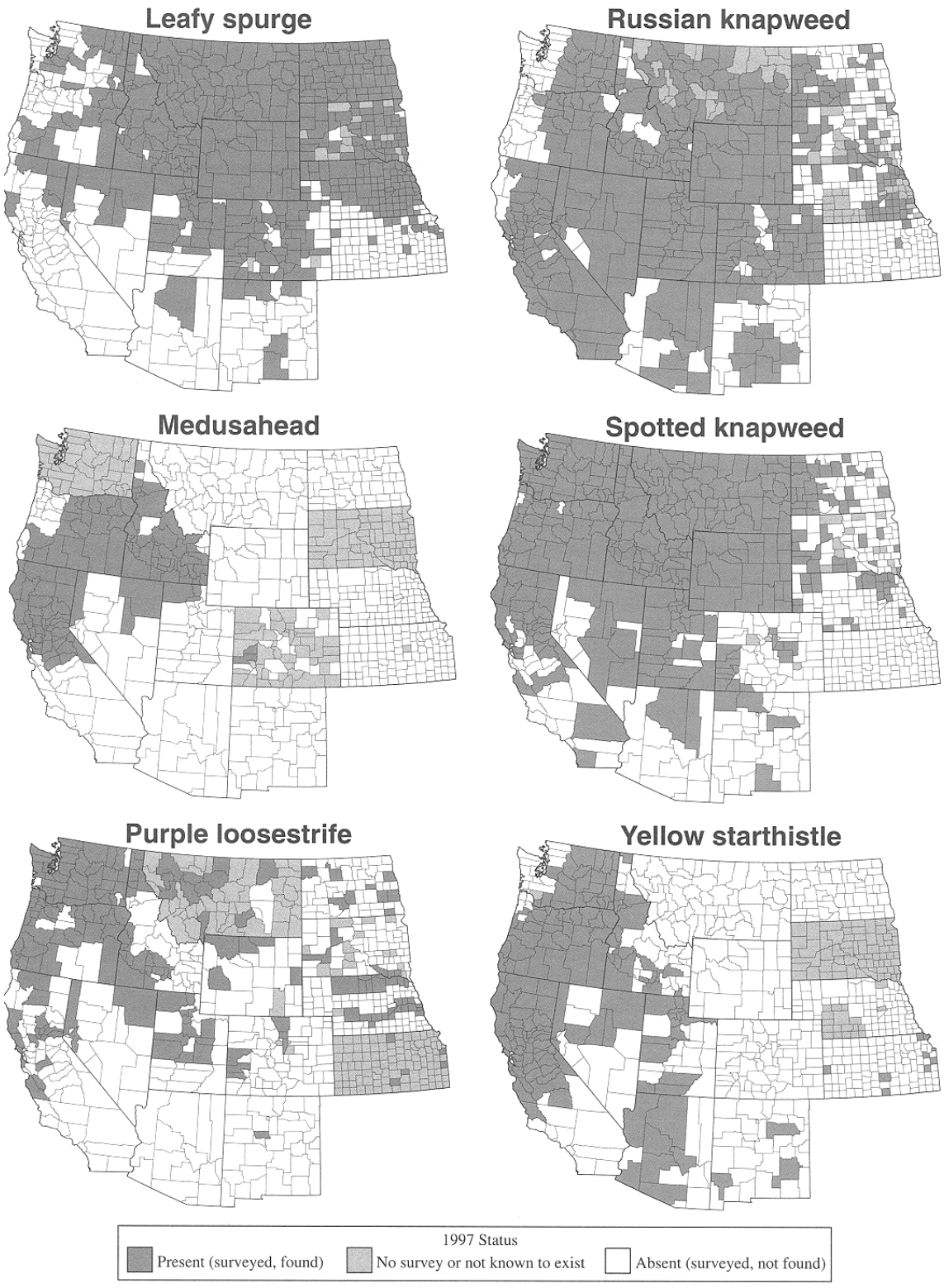

Figure 2. Areas of infestation by some invasive plant species in rangeland, wildland, aquatic, and riparian ecosystems in the western United States (Shelley and Petroff, 1999).

opportunities. About three-quarters of all domestic animals depend on grazing lands. Many ranges have been used for domestic stock grazing for over one hundred years and, as a result, the plant composition has greatly changed from the original ecosystems. For example, many western rangelands previously dominated by perennial bunchgrasses have been converted to annual grasslands that are susceptible to invasion by introduced broadleaf weeds. Over 300 species have been identified as rangeland weeds in the United States and many of these cause significant ecological and economic damage. Some of the most destructive are described in this paper (Figure 2).

Leafy spurge (*Euphorbia esula*)

Leafy spurge is an aggressive long-lived and deep-rooted perennial. It was introduced to North America from Eurasia in 1829. By the 1900s, leafy spurge had escaped and spread by seed and vegetative fragments throughout much of the western United States. It currently infests over three million acres in 29 states. Leafy spurge is adapted to a wide variety of sites, from riparian zones to dry hillsides, enabling the weed to rapidly expand its range throughout the West. Leafy spurge infestations can reduce the grazing capacity of rangelands by over 60%. Cattle will avoid grazing even in areas lightly infested with leafy spurge. The combined economic impact of leafy spurge due to cost of control efforts and loss in forage productivity in Montana, Wyoming, North Dakota, and South Dakota alone exceeds $125 million annually. In addition to its impact on forage production, leafy spurge also degrades wildlife habitat, decreases plant diversity, competes with native plant species, and reduces land values.

Yellow Starthistle (*Centaurea solstitialis*)

Yellow starthistle is a spiny winter annual that was initially introduced around 1850 to Oakland, California, as a seed contaminant in alfalfa imported from Chile. Yellow starthistle originated from Eurasia, where it is native to Balkan-Asia Minor, the Middle East, and south central Europe. Subsequent spread was slow until the mid-1900s. By the late 1950s, the weed had invaded more than one million acres in California. Since then, yellow starthistle has spread exponentially to infest rangelands, wildlands, pastures, roadsides, and agricultural areas. Currently, yellow starthistle is estimated to infest approximately 23 million acres in the West, with 20 million acres in California alone (Gerlach, 1998). In California, there is a potential for yellow starthistle expansion from its present range to nearly 40 million acres. Outside of California, yellow starthistle has more recently become a significant problem and is rapidly expanding to its biological potential in several northwestern states including Oregon, Idaho, Nevada, and Washington. Small infestations were recently found in several areas in Montana and North Dakota. Because of the spiny nature of yellow starthistle, livestock and wildlife avoid grazing in heavily infested areas. In addition, yellow starthistle causes a lethal neurological disorder in horses known as “chewing disease.” Although no economic assessments have been conducted for yellow starthistle, millions of dollars in losses probably occur from decreased forage yield and quality of rangeland and pastures, interference with grazing, increased livestock and crop management and production costs, and reduced recreational and economic value of infested land. In wildlands, yellow starthistle reduces wildlife habitat and forage, displaces native plants, and decreases native plant and animal diversity.

Spotted knapweed (*Centaurea maculosa*)

Spotted knapweed is an aggressive perennial native to Central Europe, Russia, and western Siberia. Spotted knapweed was initially introduced into the United States in the late 1800s as a seed contaminant of alfalfa. Today it is a widespread weed problem infesting over six million acres. Although spotted knapweed can be found throughout the country, it is particularly problematic in the western states from Washington to North Dakota and south to New Mexico, Arizona, and California. In Montana alone, spotted knapweed currently infests 2.1 million acres of rangeland and wildlands and has the potential to invade up to 33 million acres. The impact of spotted knapweed on the livestock industry exceeds $42 million a year (Hirsch and Leitch, 1996). In addition, it has been shown to reduce plant diversity, increase soil erosion and stream sedimentation, and dramatically reduce wildlife habitat. For example, in a Montana study, spotted knapweed infested wildlands reduced elk use by 98% compared to an adjacent uninfested area (Sheley and Petroff, 1999).

Russian knapweed (*Acroptilon repens*)

Russian knapweed is an aggressive long-lived perennial that can form near monospecific stands in infested areas. It is native to Eurasia and was first introduced into North America in 1898 as a contaminant of alfalfa seed. Today Russian knapweed covers about 1.5 million acres and is a problem in 21 western states, particularly Wyoming, Idaho, and Utah and in some eastern states, such as Virginia. It continues to expand its range at about 8% a year on all fronts, including into midwestern, northcentral and southwestern states. Russian knapweed is unpalatable to livestock and it appears to produce chemicals that inhibit the growth of competing vegetation (Stevens, 1986), probably accounting for its complete dominance in many infested habitats. Lands have been abandoned in some areas because infestations are so expansive and pervasive. However, a more typical impact is reduction in livestock carrying capacity of the range by 50% or more. Although there are no estimates on the economic effect of Russian knapweed, it has a similar or even more significant per acre impact than spotted knapweed. Because it is a perennial and has the ability to form monocultures, the impact of Russian knapweed on ecological systems can be even more detrimental than that of yellow starthistle or other knapweeds.

Medusahead (*Taeniatherum caput-medusae*)

Among the numerous introduced annual grasses that have invaded rangelands and wildlands, medusahead poses the greatest threat. It was introduced from Eurasia into southern Oregon in the late 1800s and has since spread to cover much of the grasslands of northern California, Oregon, Idaho, and Nevada. Medusahead presently occupies over one million acres of rangeland and is expected to spread further north, south, and east. Medusahead competes aggressively with other plants and provides little forage for livestock and wildlife. Furthermore, medusahead seeds contain awns that can cause physical injury to the eyes and mouths of animals. High silica content of the foliage contributes to low forage quality and a slow rate of vegetative decomposition. Older infestations are characterized by a thick layer of thatch that excludes most native herbaceous species and native perennial grasses and retards their reestablishment. The thatch layer is highly combustible and increases the frequency of fire within these sensitive habitats. While there are no reliable estimates for the economic impact of medusahead on grasslands, infestations reduce grazing capacity for livestock and wildlife by up to 80%.

Tropical soda apple *(Solanum viarum)*

Tropical soda apple is a relatively recent arrival to the United States. It is a perennial shrub native to Argentina and Brazil that was first detected in Florida in 1987. Since then, tropical soda apple has spread rapidly throughout Florida to infest at least 500,000 acres of pasture and has also invaded about a dozen other southern states. Tropical soda apple has the potential to invade any area with a tropical or subtropical climate. The foliage and stems have numerous long thick spines and are not palatable to animals. However, grazing animals can consume fruits and transport seeds in their digestive tract to other uninfested areas. Tropical soda apple in Florida rangeland forms a dense canopy that shades out other crops and vegetation and reduces cattle production to zero (Mullahey *et al*., 1996). The impact on the livestock industry exceeds $11 million a year. In addition, hundreds of thousands of dollars are spent each year to control this pest plant in open range, pastures, and forest edges and on Florida roadsides.

Kudzu (*Pueraria lobata*)

Kudzu is one of the most recognized invasive plant species throughout the southern and eastern United States. It was first introduced as an ornamental vine from Japan in 1876 and was later used as a hay crop. In the 1930s, kudzu was widely distributed by the Soil Conservation Service for erosion control. It has since invaded more than seven million acres from the mid-Atlantic states to Florida and west to Texas. Because of its viny morphology, kudzu can climb over existing vegetation and develop into large curtain-like stands that prevent light penetration to other species. Kudzu can displace virtually all other plant species dramatically altering wildlife habitat. It can grow over road signs and buildings, obscuring vision and reducing motorist safety. The economic impact of kudzu to the public is difficult to estimate, but is likely to be in the hundreds of million dollars.

Aquatic and riparian ecosystems

Virtually every aspect of human activity relies on adequate and high-quality water resources. Invasive aquatic plants cause significant ecological and economic impacts on critical and dwindling aquatic, wetland, and riparian systems (U.S. Congress, 1993). Overabundant growth and biomass create dense surface mats that reduce light penetration to understory species and curtail water circulation, thereby reducing dissolved oxygen concentrations and water quality. These weeds can limit the growth of desirable native vegetation, alter fish and wildlife communities, and reduce overall biodiversity (Haller and Sutton, 1975; Newroth, 1985; Nichols and Shaw, 1986; Smart *et al*., 1994). Exotic infestations impair aesthetic values of water bodies; reduce property values; interfere with potable, industrial, and irrigation use of water; hinder recreational swimming, fishing, and boating; and cause indirect impacts on human health (Bergstrom *et al*., 1993; Gangstad, 1986; Gangstad and Cardarelli, 1990; Newroth, 1985; U.S. Congress, 1993).

Aquatic and riparian ecosystems are highly susceptible to invasion by exotic plants because they offer suitable habitats for a wide range of species and because they are exposed to human activities that facilitate introductions of these species. A brief discussion of some ecologically and economically important exotic aquatic pest plants in the United States follows (Figure 2 [Purple loosestrife] and Figure 3).

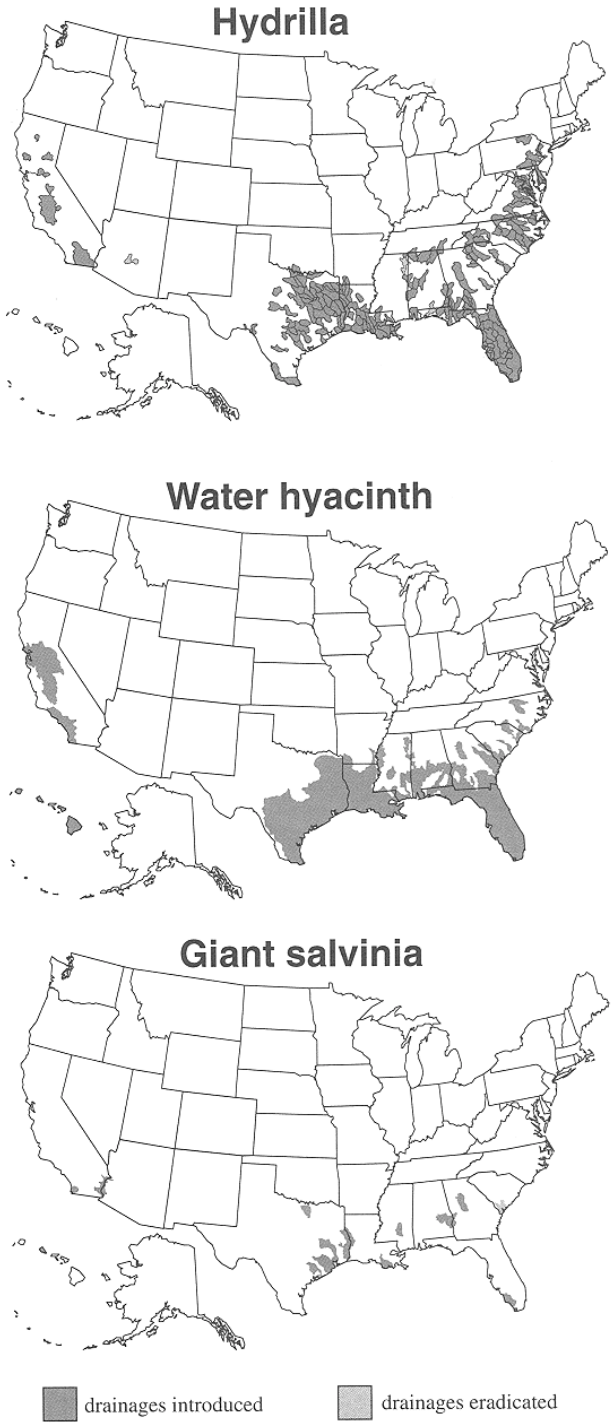

Figure 3. Areas of Infestation by some Invasive plant species in aquatic ecosystems In the United States (U. S. Geological Survey, 1999).

Hydrilla (*Hydrilla verticillata*)

Hydrilla is an Asian, African, and Australian native first found in Florida in the 1950s. This rooted, submersed plant has spread to all seaboard states from Maryland to Washington. Florida, Texas, and Alabama have the largest infestations, with a combined total of several hundred thousand acres. In the late 1970s, hydrilla colonized 500 miles of key irrigation channels in southeastern California and threatened the viability of this billion-dollar agriculture production area. Hydrilla has aggressively displaced native plants through its ability to use low light levels and by the production of long-lived tubers, which can remain viable in sediments for several years. Hydrilla has been controlled to some extent in most southeastern states since the 1960s. Specific eradication programs have been in place on hydrilla in California for the past 20 years and in Washington for the past 5 years. Costs for control of hydrilla in the United States now approach $25 million annually.

Eurasian watermilfoil (*Myriophyllum spicatum*)

Eurasian watermilfoil is a native of Europe and Asia and has been in the United States since at least the 1940s. This submersed plant now occupies lakes and reservoirs in 45 states and three Canadian provinces. In the past 15 years, watermilfoil has spread to Minnesota where it now infests 130 lakes; to Vermont, where it infests over 40 water bodies; and it was first found in South Dakota during the summer of 1999. The plant expanded from just five counties in Wisconsin in the 1960s to 54 counties in the 1990s. Eurasian watermilfoil thrives in flowing and standing waters and tolerates a wide range of temperatures. In the western United States, it has been found from as far south as the Imperial Valley in California to as far north as Washington. High-elevation sites are also vulnerable; Lake Tahoe has serious infestations of Eurasian watermilfoil. Like many aquatic submersed plants, Eurasian watermilfoil propagates primarily through vegetative growth and disperses easily by shoot fragments. The main cause for the continued spread of Eurasian watermilfoil is related to boating activities and transport on boats between aquatic sites. Several million dollars are spent each year to control Eurasian watermilfoil in the northern tier states.

Egeria (*Egeria densa*)

Egeria is a native of South America and is one of the most widely sold aquarium plants. Presently, only male plants are found in the United States, so all dispersal and spread is through cuttings and fragments, which can readily start new populations. The distribution of Egeria is not well documented; however, recent surveys show that it infests more than 3,000 acres in the Sacramento-San Joaquin Delta of California. It is widespread in Washington and Oregon as well. Impacts include interference with irrigation and boating-related activities and disruption of native habitats, including displacement of native plants. California has recently enacted state legislation with authority to spend up to $1 million annually for management of Egeria. However, the latest cost estimates for this program now project a requirement of over $2 million per year.

Water hyacinth (*Eichhornia crassipes*)

Water hyacinth, a floating tropical to semitropical plant native to South America, is considered one of the world's worst weeds, currently creating serious economic and public health problems in lakes in central Africa, Mexico, and Latin America. It was intro-

duced into the New Orleans area in the late 1800s and has spread to most coastal areas, from North Carolina, south and west to Texas and California. Water hyacinth's rapid growth and ability to smother vast, open water areas enable it to impair almost all water-related commercial and recreational activities. Dense cover formed by water hyacinth blocks light and reduces the ability of microscopic plants and rooted submersed plants to produce oxygen in the water. Vast areas invaded by this plant become uninhabitable by fish and many invertebrates. In addition, it reduces the amount of open forage areas for waterfowl. Water hyacinth continuously sloughs old roots and leaves, which greatly accelerate build up of organic matter on the bottoms of infested waters. Annual costs of management programs range from $500,000 in California to nearly $3 million in Florida. Before these programs were initiated, water hyacinth covered in excess of 500,000 acres in Louisiana and 125,000 acres in Florida. Now, control programs limit coverage to a few thousand acres.

Salvinia or giant water fern *(Salvinia molesta)*

Salvinia, which ranks as one of the most detrimental invasive aquatic plants worldwide, was not believed to be in the United States until it was discovered in South Carolina in 1995. This small population was eradicated, but the species was later found in Texas in 1997. Currently there are known populations in Alabama, Texas, and Florida, and, in August of 1999, salvinia was found in the Lower Colorado River system near Blythe, California along the Arizona border. This small fern has the capacity for prolific growth and may double its population within 3 to 4 days during summer months. The buoyancy of the plant also enables it to form floating layers of vegetation that may range from 0.5 to more than 2 feet thick. Entire lakes, ponds, and reservoirs have been completely covered with salvinia within one or two years following infestation, blocking light needed for photosynthesis by beneficial, native macrophytes and microscopic algae that form the base of the food web. Due to the dense cover that prevents light penetration and limits oxygen, areas beneath salvinia become virtually devoid of aquatic life. Waterfowl can no longer use these infested sites because their access to open water and food is lost. The salvinia infestation threatens not only the Colorado River system but also the vast acreage of irrigated crop production in Arizona, California, and Mexico. There is great potential for additional spread throughout the United States from established infestations and from nurseries and mail order suppliers that sell salvinia.

Purple loosestrife (*Lythrum salicaria*)

Since its introduction into the northeastern United States in the early 1800s, this European perennial has encroached on inland wetland and riparian systems, degrading native cattail, sedge, and wild rice communities that are critical to continental waterfowl production. Tens of thousands of acres have been infested with major populations occurring throughout the states bordering the Great Lakes, along the eastern flyway, and in western provinces in the prairie pothole region. Purple loosestrife is spreading through irrigation systems, wetlands, and river systems in the West and is found extensively in the Columbia River basin. Important native wetland plant communities have been suppressed or replaced by purple loosestrife, which is also a prolific seed producer. Purple loosestrife has showy purple spike flowers with a long bloom period, thus the spread of this weed has been enhanced by the ornamental plant and apiary industry with its use in horticultural plantings. Many large wetland areas have been so completely infested that they are beyond the scope of currently available, economically viable control techniques.

Saltcedar or tamarisk (*Tamarix* spp.)

Saltcedar or tamarisk species are native to northern Africa, the Arabian Peninsula, Iran, and India. They were introduced to the United States in Arizona, where they escaped cultivation and are rapidly infesting riparian areas. Infestations currently exist as far north as in Colorado, Wyoming, Washington, and Montana. The plant uses large quantities of water from the riparian zone and can displace native vegetation by competing for water. It also changes soil quality. The leaves of tamarisk exude salt, which accumulates on the soil surface following rainfall. This increases surface soil salinity and displaces salt-sensitive native vegetation, including cottonwoods and willows. Saltcedars also increase fire danger in riparian zones and quickly reestablish after a fire. Biodiversity has been shown to decline significantly following infestation (Hughes, 1993).

Cropland ecosystems

Hundreds of species of invasive plants are found in cropland ecosystems throughout the United States. The cost of invasive weed control in agriculture is estimated to be greater than $20 billion per year (Bridges, 1994). Weeds cause greater expenditure in fuel, equipment, labor, and control than all other pests (insects, rodents, and plant diseases) combined. The environmental and economic impacts of weeds will worsen if established species are permitted to continue to spread and new species are allowed to enter, establish, and spread throughout agricultural ecosystems. Many of these weedy species also have the ability to cross over from croplands to natural ecosystems and cause significant damage in these areas. Some of the most serious cropland weeds are described.

Velvetleaf (*Abutilon theophrasti*)

Velvetleaf thrives in highly fertile soils and is found in cultivated fields, gardens, fence rows, and waste areas. It is considered the most serious cropland weed in the United States (Stoller, 1993). It was introduced from Asia and is now widely distributed throughout the country. Velvetleaf is common in the eastern United States and the Midwest and is also found on the Pacific Coast and sparingly in the inland West, generally in warmer regions. Germination is continuous through the growing season and seeds remain viable for longer than 50 years in the soil, making control of this invasive species extremely difficult.

Yellow foxtail *(Setaria glauca [S. pumila]),* green foxtail (*S. viridis*), and giant foxtail (*S. faberi)*

The foxtails are considered the second most serious groups of weeds in U.S. agriculture and cause losses in spring-seeded alfalfa, row crops, and small grain crops. They are also found along roadsides and in other disturbed sites. Yellow and green foxtail are native to Eurasia but are common throughout most of North America, with green foxtail more common than yellow in the western United States. Giant foxtail is a native of China and occurs over a large area of the eastern United States. These plants are responsible for reductions in crop yield, increased cleaning costs, and expensive control measures.

Yellow nutsedge *(Cyperus esculentus)* and purple nutsedge (*C. rotundus)*

Nutsedges are found in cultivated soils, pastures, gardens, lawns, and waste places. Yellow nutsedge is one of the most troublesome weeds in the world. It is a native of both

North America and Eurasia and is widespread in eastern North America and along the Pacific Coast. Purple nutsedge is a native of Eurasia and is found in the southeastern United States and west to California, occasionally moving northward. The scaly rhizomes of these plants often terminate in hard tubers or nutlets, which are persistent and difficult to control. Nutsedges spread by seed and by tubers.

Johnsongrass (*Sorghum halapense*)

Johnsongrass was introduced from the Mediterranean region as a potential hay or forage crop in the 1800s and has become one of the most widespread and tenacious weeds in the United States. It was once believed to be a warm season grass but has adapted to cooler climates. Johnsongrass forms hydrocyanic acid when stressed by frost or moisture and becomes toxic to livestock. Johnsongrass is a highly invasive species that has spread rapidly and occurs in nearly every southern state. Hundreds of millions of dollars have been spent for control, while millions more have been lost from diminished crop production and difficulties associated with crop harvest operations.

Witchweed (*Striga asiatica*)

Witchweed is a parasitic plant that attaches to and devastates agronomically important crops such as corn, sugarcane, sorghum, and more than sixty other grass species. The plant originated in Africa and the Middle East and it was discovered in the United States in 1956. Witchweed is now found most prevalently infesting cropland in North and South Carolina. Because of its recognized threat to agricultural productivity, an eradication effort is currently in place in the South. More than $225 million has been spent on witchweed containment, research, and eradication to protect the $30 billion crop industry of these southern states.

Acknowledgments

Partial support for this issue paper was provided by the Aquatic Ecosystem Restoration Foundation.

References

Anderson, L. W. J. 2000. Personal communication.

Bangsund, D.A. and F.L. Leistritz. 1991. Economic Impacts of Leafy Spurge in Montana, South Dakota, and Wyoming. Agricultural Economics Report No. 275. North Dakota State University, Fargo.

Bergstrom, J. C., H. K. Cordell, R. J. Teasely, R. Souter, M. L. Messonier, C. J. Betz, M. M. Smith, and L. R. Barber. 1993. Aquatic plant coverage and outdoor recreation at Lake Guntersville, Alabama: A study of user preferences, economic values, and economic impacts. Final Report TVA/RG/WM-94005. Joint Agency Guntersville Project Aquatic Plant Management, Tennessee Valley Authority, Muscle Shoals, Alabama and U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. 210 pp.

Bridges, D. C. 1992. Crop Losses Due to Weeds in the United States - 1992. Weed Science Society of America, Champaign, Illinois.

Bridges, D. C. 1994. Impact of weeds on human endeavors. Weed Technol 8:392-395.

Bridges, D. C. 1999. General overview of weeds in crop systems. Pp. 547-566. *In* J. R. Ruberson (Ed.). Handbook of Pest Management. Marcel Dekker, Inc., New York.

Clinton, W. J. 1999. Executive Order 13112 of February 3, 1999. Invasive Species. Monday, February 8, 1999/ Presidential Documents. Fed Regist 64(25):6183-6186.

Cohen, A. N. and J. T. Carlton. 1998. Accelerating invasion rate in a highly invaded estuary. Science 279:555-558.

Corn, M. L., E. H. Buck, J. Rawson, and E. Fischer. 1999. Harmful Non-Native Species: Issues for Congress. RL 30123. Congressional Research Service, The Library of Congress, Washington, D.C. 66 pp.

Gallagher, J. E. and W. T. Haller. 1990. History and development of aquatic weed control in the United States. *In* C. L. Foy (Ed.). Rev Weed Sci 5:115-192.

Gangstad, E. O. 1986. Freshwater Vegetation Management. Thomas Publishing Company, Fresno, California.

Gangstad, E. O. and N. F. Cardarelli. 1990. The relationship between aquatic weeds and public health. *In* A. H. Pieterse and K. J. Murphy (Eds.). Pp. 85-90. Aquatic Weeds: The Ecology and Management of Nuisance Aquatic Vegetation. Oxford University Press, New York.

Gerlach, J. A. Dyer, and K. Rice. 1998. Grassland and foothill woodland ecosystems of the Central Valley. Fremontia 26(4):39-43.

Haller, W. T. and D. L. Sutton. 1975. Community structure and competition of Hydrilla and Vallisneria. Hyacinth Control J 13:48-50.

Hirsch, S. A. and J. A. Leitch. 1996. The Impact of Knapweed on Montana's Economy. Ag Econ Report No. 355. Department of Agricultural Economics, Agricultural Experiment Station, North Dakota State University, Fargo. 43 pp.

Hughes, L. E. 1993. "Me devil's own"-tamarisk. Rangelands 15:151-155.

Lonsdale, W. M. 1994. Inviting trouble: Introduced pasture species in northern Australia. Austral J Ecol 19:345-354.

Lorenzi, H. J. and L. S. Jeffery. 1987. Weeds of the United States and Their Control. Van Nostrand Reinhold Company, New York.

Muenscher, W. C. 1979. Weeds. 2nd ed. Cornell University Press, Ithaca, New York.

Mullahey, J. J., P. Mislevy, W. F. Brown, and W. N. Kline. 1996. Tropical soda apple, an exotic weed threatening agriculture and natural systems. Down to Earth 51(l):10-17.

U.S. Department of Agriculture. 1999. Safeguarding American Plant Resources. National Plant Board for the U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine, Beltsville, Maryland.

Newroth, P. R. 1985. A review of Eurasian watermilfoil impacts and management in British Columbia. Pp. 139-153. Proceedings of the First International Symposium on Watermilfoil (*Myriophyllum spictum*) and Related Haloragaceae Species, Vancouver, British Columbia, July 23-24,1985, Aquatic Plant Management Society, Clermont, Florida.

Nichols, S. A. and B. H. Shaw. 1986. Ecological life histories of three aquatic nuisance plants, *Myriophyllum spicatum, Potamogeton crispus*, and *Elodea canadensis*. Hydrobiologia 131:3-21.

North Dakota Department of Agriculture. 1996. Proceedings of the Biological Control of Weed Regulatory Summit, Denver, Colorado, April 1-2, 1996.

Pieterse, A. H. and K. J. Murphy (Eds.). 1990. Aquatic Weeds: The Ecology and Management of Nuisance Aquatic Vegetation. Oxford University Press, London. 593 pp.

Randall, J. M. and J. Marinelli (Eds.). 1996. Invasive Plants: Weeds of the Global Garden. Brooklyn Botanic Garden Publications, Brooklyn, New York. 111 pp.

Sheley, R. L. and J. K. Petroff (Eds.). 1999. Biology and Management of Noxious Rangeland Weeds. Oregon State University Press, Corvallis. 438 pp.

Smart, R. M., J. W. Barko, and D. G. McFarland. 1994. Competition between *Hydrilla verticillata* and *Vallisneria americana* under Different Environmental Conditions. Technical Report A-94-1. U.S. Army Engineer Research and Development Center, Waterways Experiment Station, Vicksburg, Mississippi.

Stevens, K. L. 1986. Allelopathic polyacetylenes from Centaurea repens (Russian thistle). J Chem Ecol 12:1205-1211.

Stoller, E. E., L. M. Wax, and D. M. Alm. 1993. Survey results on environmental issues and weed science research priorities within the corn belt. Weed Technol 7:763-770.

Stubbendiek, J., G. Y. Friisoe, and M. R. Bolick. 1994. Weeds of Nebraska and the Great Plains. Nebraska Department of Agriculture, Lincoln.

U.S. Congress, Office of Technology Assessment. 1993. Harmful Non-Indigenous Species in the United States. U.S. Congress, Office of Technology Assessment, Washington, D.C.

U.S. Congress, Office of Technology Assessment. 1995. Biologically Based Technologies for Pest Control. U.S. Congress, Office of Technology Assessment, Washington, D.C.

U.S. Department of Agriculture, Agricultural Research Service. 1991. Biological Control Quarantine: Needs and Procedures. U.S. Department of Agriculture, Agricultural Research Service, Washington, D.C.

U.S. Department of Agriculture, Agricultural Research Service. 1996. Proceedings of the Invitational Workshop on USDA Activities in Biological Control. U.S. Department of Agriculture, Agricultural Research Service, Washington, D.C.

U.S. Geological Survey. 1999. Nonindigenous Aquatic Species. Available: http://nas.er.usgs.gov/

Westbrooks, R. G. 1998. Invasive Plants, Changing the Landscape of America: Fact Book. U.S. Department of Agriculture, Federal Interagency Committee for the Management of Noxious and Exotic Weeds, Washington, D.C. 109 pp.

Whitson, T. D., L. C. Burrill, S. A. Dewey, D. W. Cudney, B. E. Nelson, R. D. Lee, and R. Parker. 1991. Weeds of the West. Western Society of Weed Science, Pioneer of Jackson Hole, Jackson, Wyoming.

Wilcove, D. S., D. Rothstein, J. Dubow, A. Phillips, and E. Losos. 1998. Quantifying threats to imperiled species in the United States. Bioscience 48:607-615.

THE MISSION OF THE COUNCIL FOR AGRICULTURAL SCIENCE AND TECHNOLOGY (CAST) *is to identify food and fiber, environmental, and other agricultural issues and to interpret related scientific research information for legislators, regulators, and the media involved in public policy decision making. CAST is a nonprofit organization composed of 38 scientific societies and many individual, student, company, nonprofit, and associate society members. CAST's Board of Directors is composed of representatives of the scientific societies and individual members, and an Executive Committee. CAST was established in 1972 as a result of a meeting sponsored in 1970 by the National Academy of Sciences, National Research Council.* *ISSN 1070-0021*

Additional copies of this issue paper are available for $3.00. Kayleen A. Niyo, Ph.D. Managing Scientific Editor. World Wide Web: http://www.cast-science.org.

Veterinary Medical Association ▪ Aquatic Plant Management Society ▪ Asae: The Society For Engineering In Agricultural, Food, And Biological Systems ▪ Association Of American Veterinary Medical Colleges ▪ Association Of Official Seed Analysts ▪ Crop Science Society Of America ▪ Entomological Society Of America ▪ Institute Of Food Technologists ▪ International Society Of Regulatory Toxicology And Pharmacology ▪ North Central Weed Science Society ▪ Northeastern Weed Science Society ▪ Poultry Science Association▪Rural Sociological Society ▪ Society For Range Management Society Of Nematologists ▪ Soil And Plant Analysis Council ▪ Soil Science Society Of America ▪ Southern Weed Science Society ▪ Weed Science Society Of America ▪ Western Society Of Weed Science