

Invasive species research in the United States Department of Agriculture–Agricultural Research Service^{†‡}

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Abstract: Invasive pests cause huge losses both to agricultural production systems and to the natural environment through displacing native species and decreasing biodiversity. It is now estimated that many thousand exotic insect, weed and pathogen species have been established in the USA and that these invasive species are responsible for a large portion of the \$130 billion losses estimated to be caused by pests each year. The Agricultural Research Service (ARS) has responded with extensive research and action programs aimed at understanding these problems and developing new management approaches for their control. This paper provides an overview of some of the ARS research that has been conducted on invasive species over the past few years and addresses both different categories of research and some specific pest systems of high interest to the US Department of Agriculture.

Published in 2003 for SCI by John Wiley & Sons, Ltd.

Keywords: invasive species; weeds; insect pests; plant protection; pesticides; biological control; sampling technologies; host plant resistance

1 INTRODUCTION

Pests are estimated to cost US farmers and consumers over \$130 billion dollars every year¹ with the world-wide cost unestimated, but significantly greater. Even though the estimates given for the highly developed US agricultural system are not very precise, it is clear that the order of magnitude of these losses is very large and major action is warranted to reduce them.² ‘Invasive’ pests not only attack our food/fiber crops and stored products, but also affect many other aspects of our daily lives and surroundings. ‘Exotic’ insect and pest-vectored pathogens even attack humans directly³ as in the case of Asian tiger mosquitoes. Additional losses to forests, rangelands and natural areas are often unquantified but equally important, producing enormous negative impacts.^{4–6} It is clear, even without precise data, that the damage caused by pests needs to be reduced in environmentally sound ways if we are to maintain productive agricultural systems, a healthy environment and a sustainable biosphere.

These pest organisms come from many different taxa of biota (insects, pathogens, nematodes, mammals, all types of microbes, plants, crustaceans, mollusks and many other groups) and from all parts

of the world.^{1,2} Scientists and pest managers have long realized that many of these pests, are ‘non-indigenous’ to the areas where they cause the most severe damage.³ That is not to say that native organisms cannot be severe pests, but that most of our worst pest problems have been transplanted from other locales or created through human-induced processes. These ‘exotic pests’ have arrived in the USA in a variety of ways, including natural movement, purposeful introduction and inadvertent arrival as unwanted hitchhikers via the ever-increasing global transportation and trade routes.²

Various terms have been used to describe these introduced pests, a few of which have already been highlighted here to demonstrate the profusion of terminology that exists in this evolving area of biology and pest management. Most recently, these introduced, exotic, alien or non-indigenous pests have been referred to as ‘invasive species’. Although other names have been used to characterize these organisms, here I will refer to them primarily as invasive species, as this name relates to the aggressive movement of these organisms in invading new habitats, and it highlights the competitive biological characteristics that make

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[†]One of a collection of papers on various aspects of agrochemicals research contributed by staff of the Agricultural Research Service of the United States Department of Agriculture, and collected and organized by Drs RD Wauchope, NN Ragsdale and SO Duke

[‡]This article is a US Government work and is in the public domain in the USA

(Received 20 May 2002; accepted 12 August 2002)

them so invasive. To confuse us even more, although many definitions suggest that 'invasive species' are of exotic origin, not all species characterized as invasive have to be exotic. In certain circumstances, changing environmental conditions (abiotic or biotic) may alter the competitive advantage of some indigenous species, causing them to become invasive in areas where they were once benign. This can occur when a new crop is brought into an area or when other environmental factors change to alter the normal dynamics of certain organisms, stimulating them to become invasive. A widely cited example of the latter would be the expansion of native woody vegetation in the western USA, which is thought to be linked to carbon dioxide increases in the atmosphere.⁷

In February 1999, the damage caused by invasive species reached such severity that President Clinton pronounced an Executive Order (EO# 13112) creating an Invasive Species Council to help address this 'widespread national emergency'. The Invasive Species Council is jointly headed by the Secretaries of Agriculture, Interior and Transportation, and is working to coordinate federal Departments and Agencies to more effectively address invasive species control and management. EO# 13112 defines invasive species as a sub-category of 'alien species'. 'Alien species' are 'with respect to a particular ecosystem, any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem.' 'Invasive species' are those 'alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health.' Of the nearly 50 000 alien species that have been introduced into the USA,¹ many are highly beneficial and are used for agricultural crops, livestock, conservation and ornamental purposes. Clearly we must carefully determine which alien species are invasive, assess their economic costs/benefits, and determine the overall implications prior to taking action to control or eliminate any given species. In many instances, the separation of alien species from its subgroup of invasive species is clear, while in other situations that line is ill-defined, varies with the geographic area and often is in the eye of the beholder. This has caused both biological and political difficulties in addressing some invasive species while others are very clear-cut and dealt with without controversy.^{3,8}

The US Department of Agriculture clearly has significant need both to protect valuable indigenous and alien species while eliminating or reducing the impact of certain detrimental invasive species. This need covers a wide range of issues and activities across the entire geographical area of the USA, adjacent countries via the NAPPO (North American Plant Protection Organization), and in some foreign countries that are important trading partners. Since little is known of most new invasive species, this has required a substantial amount of new research on invasive organisms. This research addresses concerns

across many different commodity and program areas, from conventional agricultural and forestry production systems to newly emerging disease issues and, most recently, to the problem of bioterrorism. Some of these pest problems and threats are well known and documented while others are just emerging or anticipated.⁹ Several governmental agencies^{2,4,5,9} and private groups,^{6,8} including CAST (Council for Agricultural Sciences and Technologies)¹⁰ have provided detailed recommendations on developing new invasive species research and action plans.

USDA-Animal and Plant Health Inspection Service (APHIS) estimates that over 3000 potential pests are intercepted at the US border each year³ and that many more flow through our inspection network, where some actually become established and begin the process of invasion into crops, urban and/or natural areas.² The number of these invaders is unknown but thought to be significantly increasing over the last few decades. Once established their rates of spread vary, but seem to be increasing as well.² In response to these increasing threats, USDA has expanded its research and action programs to directly address invasive species, and to develop new technologies to control and manage these pests using a wide array of tactics, many of which have been developed by Agricultural Research Service scientists.

2 THE ROLE OF THE ARS IN INVASIVE SPECIES MANAGEMENT

The Agricultural Research Service (ARS) has responsibility to conduct research on several categories of invasive pest species and has done so since its inception. The history of many invasive species can be found in conjunction with a summary on biological control programs conducted by ARS (and its predecessor Agencies) over the past 100 years.¹¹

The primary areas of concern that ARS scientists have focused on in regard to invasive species have been crop or commodity-oriented pest-management issues, such as researching the biology and management of insect, pathogen and weed pests in traditional agricultural production systems. More recently, ARS scientists have been involved in managing invasive species in forests, wildlands and aquatic systems based on new initiatives from the White House and/or Congress. The majority of this research is coordinated under ARS National Program 304, Crop Protection and Quarantine, although other National Programs, such as Arthropod Pests of Animals and Humans (NP 104) and Plant Disease (NP 303) are also active.

A significant proportion of this ARS research is aimed at developing increased biological understanding and management schemes for invasive insect and weed pests of plants. This represents over \$100 million per year of research that addresses many different aspects of invasive species biology and control. This article provides an overview of the types of research that ARS conducts in regard to invasive species, with

a summary of research activities in this area and a brief literature summary that will help readers link up to specific ARS investigators conducting that work. It is not a comprehensive review of this broad subject matter area nor does it cover all ARS programs (there are just too many).

Although, for summary purposes, ARS research on invasive species has been grouped into several somewhat arbitrary but functional categories, most ARS projects are not restricted to one of these categories but typically take a more holistic approach to studying invasive species biology and management in and across targeted habitats and ecosystems. These categories include, but are not limited to (1) basic pest biology of the invasive species, including physiology, genetics, developmental biology and related topics; (2) population dynamics, interactions with the host through predation, parasitism, competition, population increase, spread, etc; (3) interactions with the larger environment, including weather and climatic-induced effects, and interactions with their hosts, other associated pests and non-pest species in the habitats of concern; (4) management tactics, including exclusion, eradication, host-plant resistance, biological and integrated control; and (5) habitat management, which includes managing existing crops and habitats to be more resistant to invasion, and managing future crops and habitats toward a more stable and desired structure once invasive species have been controlled. This categorization will be used to discuss both invasive arthropod and weed projects and some restricted examples of other invasive species studied by ARS scientists. Details of the research efforts mentioned are beyond the scope of this article so that the reader is advised to follow the individual citations for further information.

2.1 Basic biology of invasive species

ARS scientists often first get involved with invasive species when a new pest is detected either at the US border or once a new infestation has been found by field personnel who recognize that a new and unknown pest had been encountered. The ARS Systematic Entomology Laboratory,¹² the Systematic Botany and Mycology Laboratory¹³ or one of a number of other organismal specialists hired by ARS, may receive an urgent request to identify the agent causing new and significant damage. In some cases, these specialists have identified pest problems before they arrive to our ports and have thus helped regulatory Agencies like USDA-APHIS to restrict entry or require treatment of a commodity before or during shipment.¹⁴ In other cases, a new pest may actually become established, and a timely identification allows other ARS scientists and cooperators to take immediate action to solve the problem (see Section 2.4). Taxonomic specialists are also involved in identifying new natural enemies that are used to control many invasive pests.^{15,16}

When a new invasive species has been established, ARS scientists work to understand exactly

what the biological situation is, and how/why is it occurring.¹⁷⁻¹⁹ This problem assessment is often conducted in parallel with an immediate action program to eradicate or at least retard the spread and impact of a new invasive pest. For a comprehensive summary of an emergency action program organized by ARS to combat a newly introduced pest (*Bemisia* spp), see Henneberry *et al*^{20,21} and Gerling and Meyer.²²

New invasions of insects and diseases often require immediate action, as they spread very quickly and can rapidly increase levels of damage within one or two production seasons. Although just as devastating in the long term, invasive plants typically spread more slowly and may not need action as quickly as insect and disease invasions. However, some invasive aquatic plants, such as caulerpa and giant salvinia, are so severe that they too have stimulated immediate action.²³⁻²⁵ In any case, ARS scientists quickly begin studying the basic biology of the invasive species to determine how they feed,^{26,27} grow,²⁸ reproduce, spread and impact the commodity or habitat of concern. Some of this work is directed quickly to the ARS International Laboratories to help determine where the newly arrived pest is from and how it behaves in its country of origin.²⁹ Other times, domestically based researchers work both locally and abroad to study the new invasive species in the USA and overseas to understand its dynamics^{30,31} and to identify, collect and test natural enemies for use in classical biological control programs.³² ARS operates ten major quarantine facilities where both invasive species and their natural enemies can be maintained and studied safely.^{33,34} The most secure of these quarantine facilities is located on Plum Island, off the coast of Long Island, NY, where invasive animal diseases are studied.³⁵ This facility provides US researchers with experience in working with important animal diseases, an understanding of pathogen biology, and new control methods such as vaccines³⁶ to aid in their control, if needed.

Invasive plants and their natural enemies are studied domestically in ARS quarantine facilities in Albany, CA, Temple, TX, Gainesville and Ft Lauderdale, FL, and Frederick, MD.³³ Invasive arthropods are studied under US quarantine conditions in ARS facilities in Newark, DE, Ithaca, NY, Stoneville, MS, and Weslaco, TX. Additional smaller quarantine laboratories are available at some other ARS locations where ARS scientists and cooperators also investigate the biology of many invasive species. Work conducted in cooperation with these quarantine facilities has included determining pest biotypes and host ranges of new invasive species and their natural enemies,³⁷ determining whether the invasive organisms carry disease causing pathogens, and to investigate basic biological characteristics such as pheromone detection,^{38,39} susceptibility to limiting environmental conditions²² and other factors that might lead toward new methods of control. Additional detailed biological studies in non-quarantine laboratories are also conducted to

address a wide range of factors that may affect the success of invasive insects and weeds. These range from molecular characterization of weeds and potential control agents⁴⁰ to developing new molecular marking techniques for microbial biological control agents of invasive species.⁴¹

General biology studies of invasive pests are also carried out directly in field sites where the pest is well established. This is done primarily in cases where such studies would not interfere with eradication or emergency control procedures. Life-cycle characteristics and growth,⁴² feeding studies, molecular genetics,^{43–45} population genetics^{46,47} and other similar factors such as cultivar susceptibility⁴⁸ are often characterized in support of new long-term management practices for invasive pests.

2.2 Pest detection, population dynamics and invasive species spread

With some basic knowledge of the pest biology, ARS scientists work to develop new detection and population monitoring techniques. Depending upon the specific objectives, these methods may require the development of new pheromone traps, or optimized sampling schemes using various technologies from sweepnet sampling^{49,50} to remote sensing systems.⁵¹ The goals of such research may be oriented toward providing field specialists with low-level detection abilities to help in the eradication of highly damaging pests such as the Medfly or Asian Longhorn Beetle,⁵² to assist land managers with the data to make local field-treatment decisions for invasive insect control,⁵³ or to be used in a more general manner to track the seasonal phenology⁵⁴ or the large-scale spread of an invasive species across, for example, an area-wide integrated pest management (IPM) project.⁵⁵

Often ARS scientists are involved in assessing the population dynamics of invasive species to gain a predictive understanding of when they occur and how to control them before they cause economic damage or spread to a new critical habitat. Computer simulation models have been used extensively by ARS scientists to predict the phenology and impact of invasive species in new localities and to manage them in areas where detailed biological information is required to make correct management decisions.⁵⁶ Such models have also been used effectively in planning the use of biological controls,⁵⁷ including the application of microbial pesticides, and even for use in managing invasive pests in stored products.⁵⁸ More recently, ARS scientists have been working to link remote-sensing information, predictive models and GIS (geographic information systems) to provide larger-scale assessments of invasive species impact and spread. Using these technologies, ARS scientists hope to understand better how invasive species affect entire ecosystems and how they might be better managed on an area-wide basis.

2.3 Environmental interactions

Invasive species are known to have both direct and indirect impacts on other organisms in the

environment. They may attack, weaken and/or kill crop plants,⁵⁹ livestock or other desired/beneficial organisms. They may also produce many non-direct side-effects that further degrade habitats (crops or natural areas) or alter ecosystem dynamics in ways that further their own growth and development while limiting beneficial species.⁶⁰ Many invasive weeds, for example, may promote fire, aggressively use soil water, or pull salts from the ground to the soil surface. These characteristics may inhibit growth and development of species beneficial to agriculture and the natural environment. ARS scientists are studying these factors and how invasive species and beneficial species interact^{61,62} in both terrestrial⁶³ and aquatic^{64,65} ecosystems. ARS scientists also study how different natural enemies, say insects and pathogens, interact to cause synergistic impacts on target invasive species.⁶⁶ Both invasive plants and insects are also known to competitively displace native species, further allowing the dominance of potentially damaging nuisance species.

In many cases, the interactions of an invasive species may not be entirely negative; in fact, some invasive species were actively introduced because they have many beneficial characteristics. ARS scientists are increasingly involved in studying the benefits and risks associated with the use of alien species for many different purposes, including biological control.^{67,68} A good forage colonizer is often on the edge of being invasive, that's how and why they work so effectively to out-compete other weedy species. It is therefore a balancing act to select aggressive beneficial species that are not so aggressive that they harm or eliminate other desired vegetation. Likewise, some insect natural enemies may also have a controversial impact on related species through aggressive competition.³ Risk/benefit analysis is becoming an ever more important aspect of understanding the overall impact of alien species in a variety of agricultural uses, including plant germplasm and biological control introductions.^{69,70}

The aggressive nature of most invasive species is not the same under the varied environmental conditions that exist within and between different geographic areas. Some invasive species are limited by both biotic and abiotic factors that restrict their distribution. Others are extremely wide-ranging and are threats across large areas, including multiple states or regions of the country. ARS scientists are working to understand the environmental factors that limit invasive species populations^{71,72} and how changing conditions such as increased carbon dioxide levels and predicted higher temperatures may affect both beneficial and invasive pest species. In a rather unique situation, ARS scientists are studying how an invasive plant, saltcedar (*Tamarix* spp), may be affecting an endangered bird (the southwestern willow flycatcher), and how a biological control agent, an alien leaf beetle from China, may help this and other threatened and endangered species.^{60,73,74}

2.4 Integrated pest management tactics

The majority of ARS research in the area of invasive species is directed toward developing new pest-control technologies, and combining them into IPM programs. Since so much has been written about these control tactics in this issue of *Pest Management Science*, I will not address them here but will instead list a number of key invasive species and some management tactics that are being studied in on-going ARS research.

Although non-chemical biologically based pest-management strategies are the primary focus of ARS research, a number of ARS scientists still work to evaluate and integrate safe pesticide use into management programs. Without valuable insecticide^{75,76} and herbicide^{77,78} programs, many invasive species would never be adequately controlled, and associated biological control efforts might not be economically viable alone. ARS scientists, however, are working on many more selective and environmentally friendly pesticides that are often natural products, such as grapefruit extracts used to control invasive Varroa mites (*Varroa facolsoni* Oud) on bees⁷⁹ or kaolin particles⁸⁰ for control of invasive apple and grape pests such as the glassy-winged sharpshooter. IPM approaches that use biological control for invasive whiteflies such as *Bemisia argentifolii*, Bellows & Perrin, include the use of native predators,⁸¹ exotic beneficial parasitoids^{82,83} and fungal pathogens.^{63,84,85} In cotton production systems in the southwestern USA, entomophagous nematodes have also been used to control various lepidopteran pests, including the pink boll worm, *Pectinophora gossypiella* (Saunders).⁸⁶ The list of invasive insect pests that ARS researcher are assessing for biological control is long but two significant species, the gypsy moth *hymantia dispar* L³⁷ and the Russian wheat aphid *Dimaphio noxia*,⁴⁶ are noteworthy examples of invasive insect pests that have been aggressively pursued by ARS scientists.

In the area of weed control, classical biological control is also researched to address the management of a number of key invasive species: yellow starthistle (*Centaurea solstitialis* L),^{87,88} *Melaleuca quinquenervia*,^{62,89} salt cedar (*Tamarix* sp),^{73,74} leafy spurge (*Euphorbia esula* (L)),³³ water hyacinth (*Eichornia* sp)³³ and others.^{29,31,65,66}

Host-plant resistance has also been used effectively with many invasive species, including the use of transgenic and conventional varieties for many different types of invasive insect pests from lepidoptera,^{90–92} to aphids⁹³ and beetles.⁹⁴ Most importantly, many of these technologies have been woven together into integrate programs that are effectively being implemented in areawide IPM programs,⁹ such as those existing for both invasive weeds like leafy spurge^{9,33} and insect pests like the codling moth (*Cydia pomonella* L).^{9,95}

2.5 Sustainable habitat management

ARS scientists are working hand-in-hand with farmers and land managers across the USA to determine

what factors help define both desired and sustainable ecosystems whether these are for intensive agricultural production^{96–98} or for natural land management.^{99,100} In the western USA, from the upper great basin in Idaho, Oregon and Nevada to the Joranado Range in Southern New Mexico and the plains of Texas, ARS range scientists are testing new native germplasm and their competitive ability to withstand invasion by competitive invasive species. Determining methods of rangeland improvement and using native species to revegetate areas burned by fire or denuded by other disturbances will hopefully make critical habitats more resistant to invasion by aggressive alien species.¹⁰⁰ Native plants such as Timp Utah sweetvetch, Rimrock Indian ricegrass and Sand Hollow squirreltail (all improved native species) are being developed at the ARS lab in Logan, UT, and are being evaluated for their ability to help stop invasive species like cheatgrass from taking over critical native habitats. ARS ecologists in Reno, NV, are cooperating with other ARS scientists in the Great Basins (especially Burns, OR and Boise, ID) in taking an ecosystems approach to addressing invasive weed management. ARS ecologists have not only been studying the affects of cheatgrass invasion on native plant biology, but they have determined the importance of native gramnivores in reseeding native species like Indian ricegrass.¹⁰¹ Based on this information, recommendations have been developed to help land managers take advantage of native rodent populations in making revegetation and habitat management decisions. Other ecosystem-level projects work to optimize grazing, soil and plant interactions to minimize invasive species development and spread,¹⁰² and others are even incorporating studies on microphytic seedbeds.¹⁰³

3 CONCLUSIONS

Clearly, the efforts that ARS scientists are making to address the threat and management of invasive species is extremely large. Although these projects are well coordinated through the Agency's National Programs dealing with general pest control issues, a specific plan to address invasive species directly has not been developed. The problem of invasive species, however, is tremendous in scope, with the number of exotic organisms involved in causing detrimental invasions being very high. Unfortunately, the number of existing non-indigenous species in the USA is even larger, and many of those that have not been categorized as pests may yet cause additional problems in the future. Other potential invaders are still waiting at the doorstep for that chance in a million to move into North America and become established. Since international travel and trade seem to be further expanding, the rate of entry of new invaders is also likely to increase. In response to the threats caused by these invasive species, the ARS has been quite successful in expanding research programs one by one to address several important aspects of invasive species management. Hopefully,

these programs can be further focused into a highly coordinated effort and linked with relevant action agencies to really impact the invasive species problem.

The ARS and its teams of research scientists clearly provide one of our best lines of defense against this expanding threat. Good progress has been made to date, but we must keep up our vigilance as there is much more work to be done.

ACKNOWLEDGEMENTS

I thank the USDA-ARS National Program Staff for the invitation to write this summary article, Ms Florence Ankersmit for assisting in the collection of USDA-ARS Project Reports and citations, and all the ARS scientists who have conducted and are continuing their research on invasive pests. Without their hard work, no such article could have been written.

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