USDA

Detecting and Monitoring of Invasive Species

Plant Health Conference 2000

Acronyms and Abbreviations

AARP	American Association for Retired Persons
APHIS	Animal and Plant Health Inspection Service
AVHRR	Advanced Very High Resolution Radiometer
CAPS	Cooperative Agricultural Pest Survey
CART	Classification and Regression Trees
CCD	Charge-Coupled Device (referring to digital camera)
CEIR	Cooperative Economic Insect Report
COOL	Campus Outreach Opportunity League
CPHST	Center for Plant Health Science and Technology
CPPR	Cooperative Plant Pest Report
CSR	Complete Spatial Randomness
DA	Discriminant Analysis
DARPA	Defense Advanced Research Projects Agency of the Department of Defense (see also ONR)
EDA	Exploratory Data Analysis
EPSC	Eastern Pest Survey Committee
FAO	Food and Agriculture Organization
GIF	Graphics Interchange Format
GIS	Geographic Information Systems
GPS	Global Positioning Systems
INKTO	Insects Not Known To Occur In The United States
IPPC	International Plant Protection Convention
IUCN	World Conservation Union
LISA	Localisation Industry Standards Association, software for statistics of localisation
LORAN	Long-Range Radio Navigation, the LORAN receiver is an electronic system for identifying position
MSS	Multispectral Scanner
NAIAD	North American Immigrant Arthropod Database
NAPIS	National Agricultural Pest Information System
NAPPO	North American Plant Protection Organization
NEPSC	Northeast Exotic Pest Survey Committee
NER	Northeast Region
ONR	Office of Naval Research
OTA	Office of Technology Assessment
PNKTO	Pests Not Known To Occur In The United States
PPQ	Plant Protection and Quarantine
RF	Representative Fraction
SCOPE	Scientific Committee on Problems of the Environment
SCORE	Senior Corps for Retired Executives
SER	Southeastern Region
SPOT	SPOT Image Corporation Geographic Imagery
STS	Slow the Spread
SWPM	Solid Wood Packing Material
TM	Thematic Mapper
URL	Uniform Resource Locator
UTM	Universal Transverse Mercator
USDA	United States Department of Agriculture
VS	Veterinary Services
WHIAD	Western Hemisphere Immigrant Arthropod Database

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Introduction to the Plant Health Conference on Detecting and Monitoring Invasive Species

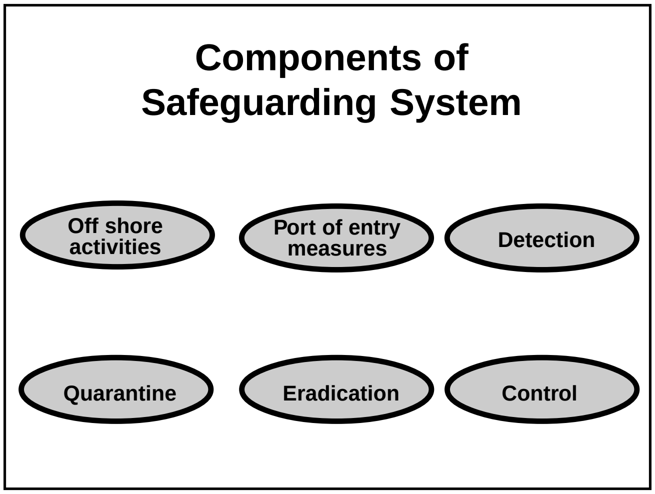
Charles Schwalbe
Associate Deputy Administrator
USDA, APHIS, Plant Protection and Quarantine

The Plant Health Conference 2000 is the first conference in what will be a series focusing on the strategic enhancement of the Plant Protection and Quarantine (PPQ) operations within the Animal and Plant Health Inspection Service of the United States Department of Agriculture. This publication is the result of the first Conference, held in October 2000 and sponsored by the Center for Plant Health Science and Technology (CPHST) in Raleigh, North Carolina.

The Center for Plant Health Science and Technology is the scientific and technical component of PPQ. It was created to interface with the research community and become an advocate for innovation in the field of plant health in service to the APHIS mission. Invasive species have been identified as a significant threat to the safeguarding of the United States of America's plant resources. New initiatives inspired by the President's Executive Order on Invasive Species emphasize the link between traditional agricultural goals in plant health and our growing concern for protection of all plant resources in America.

Safeguarding is not just another term for exclusion. It is a complementary array of risk management actions taken to prevent negative impacts of invasive species. Among these actions are detection and monitoring.

Despite general acknowledgement of the importance of detection of invasive species, this has been perhaps the least refined of the safeguarding components. One only need compare the list of serious pests found in our country through targeted detection and monitoring efforts versus the list of those found by "blundering into" it to be sobered by the state of activities in this sector. Species found by targeted approaches include the Mediterranean fruit fly and the Asian gypsy moth, because of the availability of effective detection technology and organized stakeholders in the process. Giant salvinia and the soybean aphid were found by accident, however, as are an increasing number of unwanted introductions.



With the heightened awareness of the impacts from invasive species, the Secretary of Agriculture has spoken of a "coast to coast scrubbing" to find which species are gaining a foothold in the U.S. We definitely need new approaches and technologies to achieve this level of detection. One way to improve detection is to have a better idea of what to look for by developing lists of species of particular concern.

Current lists that will be used to guide policy and focus implementation are under development with the Entomological Society of America, the Weed Science Society of America and the American Phytopathological Society. Other lists are being developed by PPQ in cooperation with nematologists. A considerable effort is going into identification of species that are not yet in the United States and that could cause significant damage to our agricultural and natural landscapes.

Are pest lists the way to improve detection programs? What would be the best use of funding for detection in the future? The Plant Conference 2000 was designed to explore new concepts and approaches for detecting invasive species and to forge new partnerships among various parts of the U.S. government, academia and private sector. The aim is to provide a forum to discuss current practices and some ideas that are still on the horizon. We wish to consider these issues in an informal and open atmosphere.

I hope that this Conference will stimulate thought and contribute to enhanced safeguarding through the Plant Protection and Quarantine programs of USDA, APHIS.

A History of Adventive Insects in North America: Their Pathways of Entry and Programs for Their Detection

Alfred G. Wheeler, Jr.
Clemson University
&
E. Richard Hoebeke
Cornell University

Abstract

In the fauna of the conterminous United States, more than 2,000 species of insects and mites are considered adventive – that is, they are nonindigenous members of our fauna. Although some of these species have become established as the result of intentional introductions, most have been accidentally introduced. Most species belonging to the latter category are noneconomic; many remain obscure even to entomologists. The small percentage of adventive arthropods that have become serious pests, especially during the 1980s and 1990s, are responsible for a heightened interest in problems caused by invasive species. In our overview of the history of immigrant arthropods in North America, we emphasize plant-associated insects, mainly phytophages. We review the various adjectives that often are applied to non-native species (e.g., adventive, exotic, foreign, immigrant, introduced, nonendemic, nonindigenous), the principal pathways or modes of introduction, the insect groups that can be considered characteristic of each pathway, and the geographic origins of our immigrant fauna. Also discussed are legislation enacted to limit the entry of exotic pests, the federal agencies responsible for excluding such pests, and federal and state initiatives and surveys that involve the detection of immigrant species.

Changes in the ranges of plants and animals are natural events and should be considered normal. Tectonic activity led to mass interchanges of biotas during the last 20 millions of years. Further dramatic changes in distributions occurred during the last 10,000 years at the end of the Pleistocene ice ages (Lodge, 1993). Yet in only a few hundred years, modern humans have moved plants and animals, both intentionally and accidentally, across previously insurmountable barriers such as oceans and mountain ranges (D'Antonio & Vitousek, 1992; Mack et al., 2000). Human effects on the North American insect fauna can be likened to those of the Pleistocene glaciers (Howden, 1969). Just as anthropogenic influences have accelerated the background rates of biotic extinctions (e.g., Wilson, 1992), human colonization has substantially increased the magnitude of invasions by non-native species.

Although it is now realized that Asian stone-age humans affected North American ecology (Krantz, 1970; Martin, 1973), their impact was minimal compared with that effected by the European colonists. Because stone-age humans were not technologically advanced, they were incapable of transporting large numbers of plants and animals (Mattson et al., 1994). But modern humans, with the capacity for rapid international travel and global redistribution of species, threaten to homogenize the Earth's biota (e.g., Soulé, 1990; Baskin, 1996).

Among the threats to species that are imperiled or are of special concern, impacts from invasive species rank second only to habitat destruction and fragmentation (Wilson, 1992; Wilcove et al., 1998). In U.S. National Parks, invasive species pose the greatest threat to native biodiversity (Devine, 1998). Many of the approximately 4,500 non-native species that have become established in the United States (U.S. Congress, 1993) – Pimentel et al. (2000) place the number at 50,000 – have adverse effects on agroecosystems, public health, social behavior, and natural systems. Nonindigenous species in the United States are estimated to cause economic and environmental losses of nearly $140 billion annually, with non-native insects responsible for an estimated $14 billion in annual crop losses (Pimentel et al., 2000).

Elton (1958) realized that invasive species or “ecological explosions” represent an important component of global environmental change, as Vitousek et al. (1996) pointed out. Even so, the threats to biodiversity and human health from alien species are perceived as less significant than those posed by genetically modified organisms, perhaps unduly. Concern over an increasing homogenization of the world’s biota led to the United Nations–Norway Conference on Alien Species in 1996. Solutions to the invasive species problem are also being pursued by groups such as the World Conservation Union (IUCN) and the Scientific Committee on Problems of the Environment (SCOPE), an effort by the International Council of Scientific Unions (Baskin, 1996). In addition, a new international journal, *Biological Invasions*, began publishing in 1999. A heightened interest in invasive species in the United States is evidenced by recent articles on the subject in journals such as *American Scientist*, *BioScience*, *Ecology*, and *Science* and in newspapers such as the *New York Times* and *Wall Street Journal*, as well as by the appearance of books such as *Life Out of Bounds: Bioinvasion in a Borderless World* (Bright, 1998), *Alien Invasion: America’s Battle with Non-Native Animals and Plants* (Devine, 1998), and *Nature Out of Place: Biological Invasions in the Global Age* (Van Driesche & Van Driesche, 2000).

Ecologists increasingly are including exotic species in their research; largely anecdotal information is giving way to data derived from quantitative and theoretical studies (e.g., Kareiva, 1996). As Lodge (1993) pointed out, research on the biological characteristics and ecological effects of invasive species can shed light on issues such as the importance of competition, predation, and keystone species, as well as other aspects of community assembly. Although ecologists have attempted to identify biological attributes shared by successful invaders, we still lack a general or comprehensive theory of invasion ecology (Lodge, 1993; Niemelä & Mattson, 1996; Mack et al., 2000). Research eventually might enable invasion ecology to become a predictive science (Kareiva, 1996), despite the complexity of interaction between communities and species and the unpredictability inherent in the outcome of a particular invasion event (Turnbull, 1967; Lodge, 1993; Ruesink et al., 1995).

Our look at invasive species in North America will focus on only one group of organisms, the insects. After briefly considering terminology in relation to non-native species, we will examine three aspects of the history of adventive insects in North America: interest in and studies on our immigrant fauna, the major pathways or modes of introduction for adventive insects, and selected detection initiatives and surveys for exotic insects. Excluded from this historical overview are natural range extensions, transport of insects by air currents, and non-native species introduced for biological control.

Terminology

Species sometimes are categorized either as native or non-native in the absence of convincing biogeographic data (Carlton, 1996). Relatively few sizable insect groups have been analyzed with respect to the biogeographic status of their component species in North America (Wheeler & Henry, 1992). The difficulty of deciding whether a particular species is native to a region or not was addressed by Lindroth (1957), who applied several criteria to the question: historical, geographical, ecological, biological, and taxonomic.

A summary of the characteristics of immigrant arthropods and guidelines for determining an adventive status were provided by Whitehead and Wheeler (1990). Some cosmopolitan, synanthropic species are now so naturalized in our biota that they appear to be native. The origin of some species is equivocal. Species that are neither demonstrably native nor introduced have been termed *cryptogenic* (Carlton, 1996).

The terminology pertaining to plants and animals that are not native to a region has been applied inconsistently. Species that are not native have been variously classified as adventive, alien, exotic, foreign, immigrant, introduced, nonendemic, and nonindigenous. These terms, however, are not strictly synonymous. Even the term *invasive species* sometimes is used to refer to any non-native species, but not all invaders become harmful. Generally this term is reserved for non-native species that cause economic or environmental damage or impair human health. From a conservation biology perspective, invasive species are those that invade natural communities, displace native species, and tend to dominate ecosystems.

Ichthyologists have attempted to standardize the terminology pertaining to non-native fishes (Shafland & Lewis, 1984), but terminology has not been standardized for insects (Frank & McCoy, 1990). The term *nonindigenous*, which is more neutral and general than most others used to denote the concept of “not native,” was adopted by the Office of Technology Assessment in its report on harmful non-native species in the United States (U.S. Congress, 1993). We will use the words *nonindigenous* and *adventive* in the following discussion. Frank and McCoy (1990) suggested that the word *introduced* be restricted to those species that are deliberately or intentionally introduced for biological control or other purposes. Such usage, however, conflicts with that adopted by the International Plant Protection Convention: the entry of a pest [through any means] resulting in its establishment[1].

Historical Interest in Adventive Insects

The record of Old World insects in colonial America is scant. As Turnbull (1980) pointed out, the early colonists were mostly concerned with their own survival and the rigors of "taming and civilizing a wild and often inhospitable continent." Although the colonists were aware of damage by insects, they usually did not refer to them specifically when mentioning damage to crops (Webster, 1892). Even in more recent times, our nonindigenous insects tend to be neglected, except those species that assume importance as pests. Bates (1956) commented on the neglect of our non-native fauna, a neglect he felt extended to applied entomologists, ecologists, and zoogeographers.

The early years. Insects accidentally introduced from the Old World are believed to date at least from the landing of the Mayflower in 1620 (Sailer, 1978). Only those species that could survive a long sea voyage were likely to be introduced and to become established (McGregor, 1973). The long voyages, in the words of Gibbs (1986), "imposed an inadvertent form of quarantine long before quarantine was formally practised."

Among early-colonizing insects were those associated with stored products and with humans and their domestic animals. Crop pests probably were not among the earliest invaders because the length of travel hindered their establishment. Insects apparently had little effect on the subsistence-level agriculture of the colonists. Crops in the first American colonies thus were "amazingly free" of the insect pests that plague modern agriculture (Popham & Hall, 1958). Even though adverse conditions prevented early colonization by most Old World insects, some crop pests entered North America and became established (Sasscer, 1940).

By the end of the 18th century, the United States had become home to Old World crop pests such as the codling moth and Hessian fly; human ectoparasites such as the bed bug and lice; and the housefly, horse bots, stable fly, and other species associated with livestock (Herrick, 1929; Sasscer, 1940; McGregor, 1973; Sailer, 1978, 1983). An estimated 13 species became established during 1600–1699 and an additional 17 species during 1700–1799 (McGregor, 1973).

The need for national quarantine legislation. Despite the expansion of agriculture and development of commerce that by 1800 had encompassed much of the world, the number of nonindigenous insects increased slowly in the United States until about 1860 (Sailer, 1978). By the mid-19th century, prominent entomologists such as Asa Fitch and Townend Glover had begun to express concern about the increasing number of pests of Old World origin (Sailer, 1978; Wheeler & Henry, 1992). An increase in steamship travel after the American Civil War facilitated the shipment of living plants, which led to the introduction and establishment of additional plant pests. Some European countries began to restrict the free exchange of plant material by the last quarter of the 19th century (Sasscer, 1940; Adamson, 1941). The United States, however, was one of the last major nations to adopt restrictive legislation (Marlatt, 1911), even though it had enacted public health laws years earlier (Sanderson, 1906). Howard (1895) referred to the passage of quarantine laws in the United States as a "crying need of the ... time." It was not until 1912 that the United States adopted plant-quarantine measures, and it was not until 1920 that the Plant Quarantine Act of 1912 was fully implemented (Sailer, 1978). The struggle to obtain national legislation aimed at limiting the importation of plant pests is related by Howard (1930, 1933), Marlatt (1911), and others (see Wheeler & Henry, 1992). Legislation was opposed by large importing nurseries (Wheeler & Nixon, 1979) and the Ladies' Garden Clubs of America (Marlatt, 1953).

It was only because a "continuous, persistent procession" (Herrick, 1929) of nonindigenous insect pests threatened U.S. agriculture that our adventive insect fauna began to receive appreciable attention. Among the Old World pests that commanded public notice and forced Congress to pass restrictive legislation were the browntail moth, gypsy moth, and San Jose scale (Felt, 1909).

The extent of our nonindigenous insect fauna. Until relatively recently, no attempt was made to compile a list of adventive insects known from North America, although Pierce (1917) listed 103 nonindigenous insect species in the United States, and Smith (1929) referred to 81 adventive insects that were among the most harmful U.S. plant pests. Bates (1956) noted the difficulty of obtaining information on the number of insect species adventive in the United States and in other faunas. Ross's (1953) estimate of 1,000 such species stood until McGregor (1973) listed 1,115 species for the continental United States. Sailer (1978)

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[1] Establishment is defined as the "Perpetuation for the foreseeable future, of a pest within an area after entry." Both definitions are from the International Standard for Phytosanitary Measures No. 5, Glossary of Phytosanitary Terms, 1999. IPPC/FAO, Rome.

provided a more precise figure of 1,385 nonindigenous insect and mite species for the 48 contiguous states, which he soon revised to 1,683 (Sailer, 1983). More recent estimates of the number of nonindigenous insects are 2,000 (U.S. Congress, 1993; Niemelä & Mattson, 1996) and 4,500, consisting of 2,000 in the continental United States plus 2,500 in Hawai'i (Pimentel et al., 2000). Nonindigenous insects represent only 1–2% of our insect fauna, yet they account for about 50% of losses to U.S. agriculture and horticulture (Marlatt, 1911; McGregor, 1973; Niemelä & Mattson, 1996).

Pathways of Introduction

The modes or pathways by which adventive insects enter the United States are dynamic: they change with technological advances that affect commerce and with changes in the commodities that move in commerce. Stowaways have been a source of nonindigenous insects since the days of the early sailing ships (Swain, 1952; Sailer, 1978). As late as 1929, the entomologist J.G. Myers was able to record 41 arthropod species from a rice ship trading from Burma to the West Indies. The insects he found on board included three cockroach species, a bed bug, a flea, ants, various stored-product pests, and the house fly (Myers, 1934). Stowaways continue to be problematic aboard airplanes and other means of conveyance.

General modes of entry recognized by Plant Protection and Quarantine of the USDA's Animal and Plant Health Inspection Service are (J.F. Cavey, APHIS, PPQ):

- baggage
- cargo, including air and maritime and permit vs. general cargo
- mail
- and conveyances such as airplanes, railroad cars, ships, and trucks.

The following account includes pathways that were more important historically, for example, ship ballast and nursery stock, as well as current pathways such as solid wood packing material and unprocessed logs and timber. Certain high-risk pathways such as airline cargo, ballast water, ship hulls, and used tires will not be discussed. Readers interested in changes in proportional representation of the various insect orders through time should consult the works by Sailer (1978, 1983); an overview of the ways in which insects enter the United States was given by Swain (1952).

Ship ballast. Throughout much of the 1800s, ship ballast traffic allowed numerous soil-inhabiting organisms to be introduced. The role that ship ballast played in the unintentional introduction of certain insect groups, especially Coleoptera, as well as other organisms (millipedes, centipedes, and isopods) associated with soil, was thoroughly researched and reported by Lindroth (1957). The insects that were most likely to be introduced with ballast included the ground beetles (Carabidae), rove beetles (Staphylinidae), weevils (Curculionidae), some sawflies (Tenthredinidae), and ants (Formicidae).

Records indicate the regular use of ballast on board sailing vessels of the North Atlantic trade routes in the 17th and 18th centuries (Lindroth, 1957). Ballast material typically consisted of soil, sand, stones, bricks, mortar, and other rubble obtained from the vicinity of the wharves of Europe, and was delivered on shore in great quantities at ports in Newfoundland, the Canadian Maritime provinces, and New England. Lindroth (1957) also demonstrated, after examining old port records, that the majority of ships engaged in North American trade sailed from a limited number of ports in southwestern England. He compiled a list of 638 species and subspecies of insects common to Europe and North America, and showed that most of the species included in this list that were introduced into North America also occurred in southwestern England. Lindroth (1957) further stated that "Newfoundland more than any other part of North America has received an introduced element of animals and plants from Europe."

After 1880, evidence suggests that soil ballast no longer played as significant a role in introducing additional species from Europe. Shortly after the Civil War, however, America saw an increase in trade with various South American countries. With an increase in South American trade, a number of important pest species began to arrive, again via soil ballast, in the vicinity of some southeastern and Gulf Coast ports. Such pests included fire ants (*Solenopsis* spp.), mole crickets (*Scapteriscus* spp.), white-fringed beetles (*Graphognathus* spp.), and the vegetable weevil (*Listroderes costirostris obliquus*) (Sailer, 1983).

Nursery stock. Living plants were not a significant source of Old World insects during the era of the sailing ships. Seeds and plant parts accounted for the establishment of some adventive species, but living plants were unlikely to survive long sea voyages. As Fogg (1974) noted, plants were "at the mercy of sailors who treated them with neglect, if not contempt."

In 1834, the English physician Nathaniel Ward developed a closed case that allowed growing, rather than dormant, plants to be shipped long distances. His case, eventually referred to as the Wardian Case, resembled "a miniature, nearly air-sealed greenhouse" (Lemmon, 1968) or terrarium (Etter, 1973).

Also facilitating the shipment of nursery stock was the advent of steamship travel in the 1840s. Demand for fruit trees and ornamental plants increased in the northern states after the Civil War (Sailer, 1978, 1983). Vast numbers of plants arrived at U.S. ports in the years before any plant-quarantine laws. Maryland received some 3.2 million seedlings, plants, and trees in 1910 alone (Symons, 1911), and a similar number of plants arrived in Pennsylvania in 1914 (Surface, 1915). Much of the plant stock was of inferior quality – packed by the thousands in a single case and often infested by insects (Howard, 1912). The United States became "a dumping ground for refuse stock" that was sold at auction or at low prices (or sometimes given away) by large department stores in New York and Philadelphia (Marlatt, 1911).

Insect groups particularly susceptible to movement with nursery stock were scale insects, aphids, leafhoppers, and plant bugs (Adamson, 1941; Sailer, 1978, 1983; Hamilton, 1983; Wheeler & Henry, 1992). The gypsy moth and browntail moth were among pests introduced with nursery stock. Smith (1929) mentioned that sawflies also are predisposed to successful introduction with plant shipments.

Solid Wood Packing Material. Detection of the Asian longhorned beetle in New York and Chicago (Haack et al., 1996, 1997; Cavey et al., 1998) emphasized the importance of solid wood packing material (SWPM) as a vehicle for the unintentional importation of exotic forest pests. Low-grade wood and other wood products, used to support, brace, or package goods and commodities during shipment from abroad, provide an excellent pathway for the global movement of bark and wood-boring beetles (URL: http://exoticpests.apsnet.org/Papers/allen.htm). The common shoot beetle (*Tomicus piniperda*) is believed to have been originally introduced into the Great Lakes region in wooden dunnage that had been discarded at Great Lakes ports since the 1980s (Haack, 1997). Another dunnage hitchhiker is the spruce bark beetle (*Ips typographus*). An important European pest of spruce, it has been repeatedly intercepted at several U.S. and Canadian ports in the past decade, and it remains a threat if it enters and establishes in our native forests.

The immature stages of adventive forest pests can often complete their development in crating, pallets, large-dimensional wood spacers and skids, and dunnage (rough-sawn timber often with bark attached). They subsequently emerge as adults after commodities have arrived at their final port or warehouse destinations. Most SWPM is considered a by-product of international trade and is generally discarded. If these packaging materials are discarded in or near natural forested lands, or urban forests, the likelihood for introduction and establishment of these non-native forest pests is greatly enhanced.

In both the United States and Canada, numerous quarantine or potential quarantine pests are repeatedly intercepted in these aforementioned wooden articles originating from Asia, Europe, and South America. Commodities such as wooden wire and cable spools from China, and wooden crating with ceramic tiles and marble or granite landscape stones from Brazil and other foreign ports, are frequently found to be infested with live wood-boring insects (primarily Cerambycidae and Scolytidae) in the United States and Canada (Haack & Cavey, 1997, 1998; also URL: http://www.pfc.cfs.nrcan.gc.ca/biodiversity/exotics/index_e.html).

Unprocessed Logs and Timber. The importation of unprocessed logs, lumber, and other unmanufactured wood products into the United States is a primary pathway for transporting wood borers, bark beetles, defoliators, and other major forest pests. This pathway should always require a comprehensive risk analysis because it alone could be responsible for the introduction of serious forest pests and diseases. For example, Siberian timber imports represent a potentially high-risk pathway for a number of serious pest organisms. Siberia harbors almost half the world's softwood timber supply. Since the late 1980s, several U.S. timber brokers and lumber companies, running low on domestic sources, have been negotiating for the importation of raw logs from Far East ports to our West Coast sawmills (U.S. Congress, 1993). The risks of introducing pests such as the Asian gypsy moth (*Lymantria dispar*) and the nun moth (*Lymantria monacha*) with imported larch (*Larix* spp.) timber and logs from Siberia is extremely high. The establishment of these pests in Northwest forests could trigger an ecological catastrophe, with potential losses amounting to $35–58 billion (U.S. Congress, 1993). During the past 100 years, raw wood, nursery stock imports, or both, also have allowed several devastating pathogens to enter, such as those responsible for chestnut blight, Dutch elm disease, and white pine blister rust (U.S. Congress, 1993).

Pest Detection Initiatives and Surveys

Intercepting invading species at ports of entry is of paramount importance in protecting American agriculture from nonindigenous plant pests. We would also stress the value of detecting insects that pass through our front line of defense before they can become established over a wide area. We agree with the philosophy of Davis (1962): "Any time qualified personnel are surveying for insects, they are in a position to do some detection work." A key word here is *qualified*, for the chances of detecting an adventive species increase with a field observer's increasing knowledge of the local fauna (Hoebeke & Wheeler, 1983). Far less efficient in terms of time and money is the mass collection (e.g., by sweep-netting or blacklighting) of insects by untrained personnel, followed by a laborious sorting of specimens and the eventual recognition of any new invaders by taxonomic specialists.

Insect Pest Survey Bulletin. By the early 1920s, the USDA's Bureau of Entomology realized that rapid advances of the preceding decade dictated a change in the agency's philosophy. Apparent was a need for more comprehensive insect survey that would assemble data on pest abundance and outbreaks, weather, phenology, and other information.

In 1921 the Bureau of Entomology launched the "Insect Pest Survey Bulletin," a monthly publication on current insect conditions throughout the United States. Cooperators in this survey were state entomologists, agricultural experiment stations in the land-grant colleges, state departments of agriculture, and others. The format used in the first issue (May 1, 1921), and generally in subsequent numbers, was to arrange insect survey information by cereal and forage crops, cotton, fruit trees, truck crops, and forest and shade trees; household and stored-product pests sometimes were covered. Special reports, for example, on insect outbreaks, were issued shortly after the information was received. Also appearing irregularly were supplemental reports on the status of certain adventive pests, such as the European corn borer. In 1923 (Vol. 3), a monthly review of insect conditions in Canada was added.

Published through 1942 and often overlooked by entomologists as a source of qualitative, historical information, the Insect Pest Survey Bulletin provided new state records (though not identified as such), notes on extent of crop damage, and biological tidbits such as adult emergence and oviposition times. At the end of each year's volume is an index of scientific names, cross-referenced to common names, that facilitates the retrieval of information.

Special Port-of-Entry Survey during World War II. An increase in wartime traffic, with the inevitable relaxation of quarantine vigilance, increased the likelihood of non-native pests entering the country. In June 1943 a special survey, financed by Presidential Emergency Funds, was initiated for ports of entry. The U.S. periphery (except the border with Canada) was divided into four districts: Pacific Coast, Mexican Border, Gulf Coast, and Atlantic Coast. Nearly year-round surveys were conducted in southern California, the Rio Grande Valley of Texas, and in other states that border the Gulf of Mexico. Inspection was most intensive in the case of field crops, home gardens, orchards, and ornamentals; attention also was given to certain wild plants that are members of families closely related to important crop plants. Special surveys were carried out for the Mexican rice borer in the Imperial Valley of California and adjacent regions of Arizona and Mexico and for three adventive wood-boring beetles (two bostrichids and a cerambycid) that were not known to be established in the United States.

The "Special Survey for Insect Pests and Plant Diseases in the Vicinity of Ports of Entry" was the largest pest survey ever conducted in the United States. Under the supervision of the Bureau of Entomology and Plant Quarantine, the survey involved 92 persons (82 of whom were professional) for 25 months (June 1943–June 1945). Inspections amounted to more than 63,000 man-hours. Nearly 32,000 lots of insects and more than 5,600 samples of diseased plants were submitted to specialists for identification. Survey accomplishments included the first U.S. records of at least 41 insect species and 17 plant pathogens, plus the collection of 128 insects and 28 phytopathogens new or probably new to science. The rearing of immature insects also resulted in considerable new information on host plants, life history, and distribution, as well as specimens representing about 140 species of parasitoids, many of them undescribed. Although few serious plant pests were detected, seven insect species considered injurious in the West Indies and countries south of the Mexican border were found in Florida and Texas.

Many entomologists and plant regulatory specialists no doubt are unfamiliar with this special port survey undertaken during World War II. Information in the foregoing paragraphs was taken from the publications by Sasscer (1946), Haeussler and Leiby (1952), and USDA (1960).

CEIR/CPPR/Plant Pest News. In April 1951, the USDA–APHIS–PPQ developed a plan for "strengthening cooperative insect pest surveys in the United States," noting that agricultural workers of the country needed a more current and complete nationwide system of cooperative economic insect reporting. What resulted was the "Cooperative Economic Insect Report" (CEIR), a weekly summary of the current status of economically important insect pests from across the United States.

The first CEIR report was issued on July 31, 1951, and publication ceased with volume 25 in 1975. It was replaced by the "Cooperative Plant Pest Report" (CPPR) on January 30, 1976. This expanded reporting system included other pests of plants and animals, such as diseases, snails and slugs, and weeds. This publication was distributed weekly to federal and state agencies, universities, farmers, and others interested in containing or controlling pests in the United States. The data included in this publication were compiled from reports submitted by cooperating state, federal, and other agricultural specialists. A "special reports" section in the CPPR documented any new insect detections—that is, any adventive species—in the United States. The CPPR terminated with volume 5 in October 1980.

In March 1981, the newsletter "Plant Pest News" was initiated. Directed toward plant-protection activities, it was published instead of the CPPR, which had dealt mainly with domestic pests. This newsletter instead emphasized 1) significant new U.S. records, 2) alerts to impending danger of new pests, 3) first finds of unestablished, economically important pests in regions distant from infested/infected areas in the United States, and 4) significant interceptions at U.S. ports of entry. The last of these "Plant Pest News" reports appeared in August 1981.

A particularly informative series of short papers appeared periodically in the CEIR, CPPR, and the APHIS 81 series. They detailed economic importance, geographic distribution, hosts, life history, and descriptions of various important exotic insect and mite pests, snails, slugs, and fungal, bacterial, and viral plant diseases. This compilation of papers was called "Insects Not Known to Occur in the United States" (INKTO) and "Pests Not Known to Occur in the United States" (PNKTO). It was initiated early in 1957 to help strengthen detection programs against foreign insect pests not known to be established in this country. As of January 15, 1991, at least 267 individual exotic pest reports were indexed in a directory to INKTOs and PNKTOs.

The McGregor Report. In 1971, the U.S. Department of Agriculture established an eight-member task force, chaired by Russell C. McGregor (Berkeley, CA), to review the effectiveness of plant quarantines in preventing the entry of exotic pests into the United States, and to define the risks associated with the potential entry and establishment of specific exotic pests and diseases. A final evaluation report entitled "The Emigrant Pests" but commonly called "The McGregor Report," was completed in 1973 and submitted to the Administrator of USDA, APHIS. It provided 1) an analysis of the threat exotic pests pose to the environment and agriculture of the United States, 2) an evaluation of the USDA's inspection and quarantine programs, and 3) a proposal for increasing plant-health protection on a global basis (McGregor, 1973). Among the various recommendations made by this task force, the principal ones included 1) that regulatory officials continue to recognize and emphasize the worldwide movement of pests through global trade and that measures against foreign shippers be strengthened, 2) that exclusion activities against high-risk pests of foreign origin that are not yet established be emphasized, 3) that more information on the distribution, survival potential, and colonization characteristics of exotic pests be acquired to reduce biological uncertainty associated with these potential invaders, and 4) that the shared responsibility of the public and private sectors in protecting American agriculture receive more attention. These recommendations were further evaluated by an APHIS Evaluation Task Force in 1974 and again in 1985 by a Blue Ribbon Panel (a study of agricultural quarantine inspection programs of USDA, APHIS, PPQ). As a part of this overall effort, the task force, led by Reece Sailer, also compiled an extensive list of more than 1,100 immigrant insects and related arthropods established in the United States (see also above discussion under Historical Interest in Adventive Insects).

High Hazard Pest Survey. America's first lines of defense against the unintentional entry of any exotic insect pest traditionally have been plant-quarantine restrictions imposed at the ports of entry and the rigorous inspection of goods and cargo. Interceptions of significant plant pests at the major ports are commonplace; each year, the total number of interceptions usually exceeds 30,000–40,000. America's second line of defense has been the implementation of effective and thorough survey and detection efforts to locate new pests that may have escaped inspections at entry points.

Across the country, many state departments of agriculture employ a network of insect survey programs. In addition to these state surveys, a program for early pest detection was initiated by the USDA, APHIS, PPQ in June 1977. The primary objective of this exotic surveillance, coined the "High Hazard Pest Survey," was the detection of any foreign plant pest of importance to American agriculture at potential introduction sites before their widespread establishment. Historically, more than 90% of all exotic plant pest introductions have occurred near major seaports and airports, or near border regions. These areas surrounding the major ports have become prime targets for federal inspectors, and have assumed "high-hazard" status. These high-hazard designations are loosely defined as any area within a 100-mile radius of major ports of entry. Special emphasis, in terms of survey and collection of specimens, was placed on cultivated tracts of land within this 100-mile zone. Actual collecting sites (e.g., airports, military establishments, railroad yards, truck terminals, etc.) were chosen on the basis of ecology, history, exposure, and destinations.

One of the centers of identification for the High Hazard Pest Survey was located at Cornell University, where the second author was the principal identifier of specimens submitted from the Northeast region. As a result of this single pest-survey initiative, as many as eight non-native insect species were identified for the first time from the Western Hemisphere or North America. Most of these species appear to be innocuous and pose little, if any, threat to agriculture, but they nonetheless represented new records of adventive species in North America. One coleopteran, the mangold flea beetle (*Chaetocnema concinna*), a minor pest of various chenopodiaceous crops in Europe, was among those first-time discoveries. Several other centers of identification also identified specimens generated by this unique detection survey.

Cooperative Agricultural Pest Survey (CAPS). The Cooperative Agricultural Pest Survey is a combined effort by federal and state agricultural organizations to conduct surveillance, detection, and monitoring of agricultural crop pests and biological-control agents. Survey targets include weeds, plant diseases, insects, nematodes, and other invertebrates of importance to American agriculture, horticulture, and forestry. Components of this program include 1) survey, detection, and identification activities in the field and laboratory, 2) state-level databases on exotic pest interceptions and their subsequent distribution, 3) a national database, the National Agricultural Pest Information System (NAPIS), and 4) an electronic information exchange system. The U.S. Department of Agriculture (APHIS, PPQ) provides national and regional coordination, funding, and technical support for federal and cooperative survey projects.

CAPS evolved from an earlier initiative begun by the Intersociety Plant Protection Consortium in 1980. First known as the Cooperative National Plant Pest Survey and Detection Program, it was envisioned as a coordinating mechanism for all pest surveys in the United States. In 1992, CAPS was redirected to emphasize a set of goals and objectives more realistically suited to the available resources and to better reflect the mission of Plant Protection and Quarantine. The current goals of CAPS are to 1) detect exotic pests before they can become well established, 2) to facilitate the export of U.S. agricultural products, and 3) to collect and manage survey data from PPQ cooperative programs. All of these goals help PPQ to meet its legally mandated responsibilities (URL: http://ceris.purdue.edu/napis/caps.html).

Hoebeke–Wheeler Detection Trips. With a well-founded knowledge of the local insect fauna of the Northeast and the ability to recognize unfamiliar species associated with naturalized weeds, we have conducted our own survey and detection trips to areas in the northeastern United States and eastern Canada, including the Maritime provinces of Nova Scotia, New Brunswick, and Prince Edward Island. We emphasize nonindigenous species that have gone undetected. From 1978 to the present, we have collected in areas considered particularly vulnerable to invaders, such as industrial sites in urban settings, railroad yards, disturbed waste sites, and open fields near airports or seaports. We have visited Baltimore, Norfolk–Newport News, Boston, Philadelphia, Halifax, St. John, and Sydney. Sweeping and collecting from various non-native weeds in these high-risk sites has consistently yielded numerous first-time records of adventive insects. Our general collecting of insects in the Northeast has turned up at least 12 adventive species that were new to North America, and additional adventive species known only from a few North American localities.

Our discoveries, plus detections made during the “High Hazard Pest Survey” conducted by USDA, APHIS in the late 1970s and other federal and state surveys, have further demonstrated our inadequate knowledge of North American insects. Turnbull (1979) acknowledged our “ignorance of the recent changes in the insect fauna.”

North American Immigrant Arthropod Database (NAIAD). Known previously as WHIAD – the Western Hemisphere Immigrant Arthropod Database (Anonymous, 1986) – the computerized North American Immigrant Arthropod Database (NAIAD) began in 1980. The intent was to provide a generally accessible, computerized compendium of the vast and dispersed body of knowledge on the immigrant arthropod fauna of North America (Knutson et al., 1990). This interactive database contains 51 subject fields of core data (e.g., geographic origin, date of entry and distribution, hosts, etc.) on 1,800 species of arthropods not native to America north of Mexico. The species data files actually grew from the work of the late Reece I. Sailer that began in about 1968. He had developed a hard copy file of core data on nonindigenous insects and mites in North America and Hawai‘i (see also above discussion under The Extent of Our Nonindigenous Insect Fauna).

Northeast Exotic Pest Survey Committee (NEPSC). In 1991, the Northeast Region (NER: USDA, APHIS, PPQ) redirected its existing exotic pest-survey efforts by modifying the process by which survey targets, among pest species not known to occur in the United States, are selected. The NER appointed a committee to research and make recommendations toward accomplishing this exotic pest survey. This group, initially known as the Pest Interception Committee, later chose the name Northeastern Exotic Pest Survey Committee. The idea is to target exotic pests that are frequently intercepted at NER ports of entry and those likely to become established in the northeastern United States. Objectives of the committee are 1) to generate a list of pests frequently intercepted and to develop a plan for distributing the list to state regulatory officials and the Cooperative Agricultural Pest Survey (CAPS) community, 2) to develop criteria – winter tolerance, host specificity and availability, survey methodology, taxonomic status, destination, potential economic impact, entry potential, and establishment potential – for assessing risk and consequence of establishment of potential target pests, 3) to apply the same criteria to the list of frequently intercepted pests and rank potential targets, and 4) to select target pests, survey methods, and geographic sites for future survey efforts. In 1998, the NER joined with the Southeastern Region (SER) to accomplish these same goals for the eastern United States; this group is now referred to as the Eastern Pest Survey Committee (EPSC).

Recent Federal Recommendations and Summaries

The difficulty of keeping nonindigenous species from invading and becoming established in the United States was captured by Bright (1998): “Bioinvasion is a deeply unsatisfying policy topic. It is messy, frustrating, depressing, and unpredictable: it does not lend itself to neat solutions.” His words appeared in the same year that President Clinton issued an executive order addressing the continuing threat posed by invasive species. Here we review that Presidential Executive Order plus two important reports that may affect the way in which APHIS, PPQ attempts to prevent new, harmful pests from entering the country.

On February 3, 1999, President William Jefferson Clinton signed Executive Order 13112 on Invasive Alien Species. The order established an Invasive Species Council to be co-chaired by the Secretaries of the U.S. Departments of the Interior, Agriculture, and Commerce, and including federal agency head membership from State, Defense, Treasury, Transportation, and the Environmental Protection Agency. This executive order directed the council to “provide national leadership on invasive species” by developing a national invasive species management plan (by August 2000), which ultimately would increase coordination of federal agencies to 1) prevent introductions, 2) detect, respond rapidly, and control populations, 3) monitor, 4) restore native species and habitats, 5) conduct research and develop mitigation strategies, and 6) promote public education.

OTA Report. A 1993 report from the Office of Technology Assessment (OTA), U.S. Congress, stated that harmful nonindigenous species annually cost our nation millions to billions of dollars and cause significant and growing environmental problems. The three major focal points of this study and report included 1) an overview of the status of harmful non-indigenous species in the United States, 2) an analysis of the technological issues involved in dealing with invasive species, and 3) an examination of the institutional organization in place (U.S. Congress 1993).

Safeguarding Report. A recent stakeholder review of the APHIS, PPQ safeguarding system in the United States, entitled “Safeguarding American Plant Resources” (National Plant Board, 1999), was conducted by the National Plant Board at the request of Congress. To improve their mandated safeguarding procedures, APHIS, PPQ sought input from key external stakeholders (academia, government, industry, and non-government organizations) through a formal review process. Four areas that were examined intensively and queried by the review panel included pest-exclusion activities, pest-detection approaches, acquisition of international pest information, and the permits system.

The overriding theme of the Safeguarding Report is that in our expanding global marketplaces of today and the future, “international travel and trade have not only made borders irrelevant, but also dramatically increased the risk of invasive plant pest introductions.” The report emphasized that “recent breaches of the APHIS, PPQ safeguarding system that led to entry of dangerous invasive plant pests into the U.S. have raised concerns that current organizational policies and procedures are inadequate to execute Agency (APHIS, PPQ) functions.” Multiple introductions of the Medfly in Florida and California, and the Asian longhorned beetle in New York and Chicago, with the discovery of citrus canker infestations in Florida, all serve to demonstrate the extreme risks brought about by the expansion of global travel and trade.

The Future

We began by referring to the increasing homogenization of the Earth's biota. For some the future seems particularly dismal. Soulé (1990), for example, stated that "a blanket opposition to exotics will become more expensive, more irrational, and finally counterproductive as the trickle becomes a flood." Metcalf (1996) considered it inevitable that most of the world's worst pests will become cosmopolitan by the end of the 21st century.

C.L. Marlatt, a prominent federal entomologist, suggested late in the 19th century that a laissez-faire approach be taken to the quarantine problem. He remarked that "one may even question whether it would not be better in the long run, instead of trying to keep out injurious insects, with the necessary and mischievous restrictions on commerce of all sorts, to let such matters take their own course" (Marlatt, 1899). Important nonindigenous plant pests often do establish an equilibrium in an agroecosystem, a formerly serious invader eventually being reduced in status to only an occasional or a secondary pest (e.g., Kogan, 1982). Yet the USDA, by mandate, must continue all attempts to exclude invading organisms. Ruesink et al. (1995) advocated constraint – a guilty-until-proven-innocent philosophy of risk assessment by the USDA. The USDA, APHIS, PPQ's development of a database of potentially destructive insect invaders as an early-warning system (Entomological Society of America Newsletter, Vol. 21, No. 11, Nov. 1998), coupled with the adoption of certain recommendations in the Safeguarding Report, should help to forestall an actual cosmopolitanization of our insect fauna.

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References

Adamson, A.M. 1941. The geographical distribution of insect pests. Tropical Agriculture 18:43–47.

Anonymous. 1986. Western Hemisphere Immigrant Arthropod Database (WHIAD). Biosystematics and Beneficial Insects Institute, Agricultural Research Service, U.S. Department of Agriculture. March, 1986, 95 pp.

Baskin, Y. 1996. Curbing undesirable invaders. BioScience 46:732–736.

Bates, M. 1956. Man as an agent in the spread of organisms. In: Man's Role in Changing the Face of the Earth, W.L. Thomas, Jr. (ed.). University of Chicago Press, Chicago, pp. 788–803.

Bright, C. 1998. Life Out of Bounds: Bioinvasion in a Borderless World. W. W. Norton, New York, 287 pp.

Carlton, J.T. 1996. Biological invasions and cryptogenic species. Ecology 77:1653–1655.

Cavey, J.F., E.R. Hoebeke, S. Passoa and S.W. Lingafelter. 1998. A new exotic threat to North American hardwood forests: an Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae). I. Larval description and diagnosis. Proceedings of the Entomological Society of Washington 100:373–381.

D'Antonio, C.M. and P.M. Vitousek. 1992. Biological invasions by exotic grasses, the grass-fire cycle, and global change. Annual Review of Ecology and Systematics 23:63–87.

Davis, L.G. 1962. Contributions of plant pest control programs: the need for pest detection followups. Bulletin of the Entomological Society of America 8:59–62.

Devine, R. 1998. Alien Invasion: America's Battle with Non-native Animals and Plants. National Geographic Society, Washington, DC, 280 pp.

Elton, C.S. 1958. The Ecology of Invasions by Animals and Plants. Methuen, London, 181 pp.

Etter, H. 1973. Out of a chrysalis, a Wardian case. Morton Arboretum Quarterly 9:49–55.

Felt, E.P. 1909. Insects and legislation. Journal of Economic Entomology 2:342–345.

Fogg, J.M., Jr. 1974. The development of horticulture in America. Morris Arboretum Bulletin 25:5–9.

Frank, J.H. and E.D. McCoy. 1990. Endemics and epidemics of shibboleths and other things causing chaos. Florida Entomologist 73:1–9.

Gibbs, A. 1986. Microbial invasions. In: Ecology of Biological Invasions, R.H. Groves and J.J. Burdon (eds.). Cambridge University Press, Cambridge, pp. 115–119.

Haack, R.A. 1997. Early history and spread of *Tomicus piniperda* in North America. In: 1997 Japanese Beetle and Pine Shoot Beetle Regulatory Review: Proceedings, Louisville, Kentucky, 24–26 February 1997. USDA–APHIS, Riverdale, Maryland, pp. 146–153.

Haack, R.A. and J.F. Cavey. 1997. Insects intercepted on wood articles at ports-of-entry in the United States: 1985–1996. Newsletter of the Michigan Entomological Society 42(2–4):1–6.

Haack, R.A. and J.F. Cavey. 1998. Insects intercepted on wood articles at United States ports-of-entry and two recent interceptions*: Anoplophora glabripennis* and *Tomicus piniperda.* In: Proceedings: International Forest Insect Workshop, 18–21 August 1997, Pucon, Chile, C. Perez and C.L. Gotor (eds.). Corporacion National Forestal, Santiago, Chile, pp. 172–187.

Haack, R.A., J.F. Cavey, E.R. Hoebeke and K.R. Law. 1996. *Anoplophora glabripennis*: a tree-infesting exotic cerambycid invades New York. Newsletter of the Michigan Entomological Society 41(2–3):1–3.

Haack, R.A., K.R. Law, V.C. Mastro, H.S. Ossenbruggen and B.J. Raimo. 1997. New York's battle with the Asian longhorned beetle. Journal of Forestry 95:11–15.

Haeussler, G.J. and R.W. Leiby. 1952. Surveys of insect pests. In: Insects: The Yearbook of Agriculture 1952, F.C. Bishop (Chairman) et al. (eds.). U.S. Government Printing Office, Washington, DC, pp. 444–449.

Hamilton, K.G.A. 1983. Introduced and native leafhoppers common to the Old and New Worlds (Rhynchota: Homoptera: Cicadellidae). Canadian Entomologist 115: 473-511.

Herrick, G.W. 1929. The procession of foreign insect pests. Scientific Monthly 29:269–274.

Hoebeke, E.R. and A.G. Wheeler, Jr. 1983. Exotic insects reported new to northeastern United States and eastern Canada since 1970. Journal of the New York Entomological Society 91:193–222.

Howard, L.O. 1895. Injurious insects and commerce. Insect Life 7:332–338.

Howard, L.O. 1912. Bureau of Entomology. In: USDA Annual Report of the Department of Agriculture for Year Ended June 30, 1911. U.S. Government Printing Office, Washington, DC, pp. 111–115.

Howard, L.O. 1930. A History of Applied Entomology (Somewhat Anecdotal). Smithsonian Institution, Washington, DC, 564 pp.

Howard, L.O. 1933. Fighting the Insects: The Story of an Entomologist, Telling of the Life and Experiences of the Writer. Macmillan, New York, 333 pp.

Howden, H.F. 1969. Effects of man on the Ontario insect fauna. Proceedings of the Entomological Society of Ontario 99:51–53.

Kareiva, P. 1996. Developing a predictive ecology for non-indigenous species and ecological invasions. Ecology 77:1651–1652.

Knutson, L., R.I. Sailer, W.L. Murphy, R.W. Carlson and J.R. Dogger. 1990. Computerized data base on immigrant arthropods. Annals of the Entomological Society of America 83:1–8.

Kogan, M. 1982. Impact and management of introduced pests in agriculture. In: Proceedings of the Symposium on the Imported Fire Ant, 7–10 June 1982, Atlanta, Georgia, L. Battenfield (ed.). Environmental Protection Agency; USDA Animal, Plant Health Inspection Service, Washington, DC, pp. 226–236.

Krantz, G.S. 1970. Human activities and megafaunal extinctions. American Scientist 58:164–170.

Lemmon, K. 1968. The Golden Age of Plant Hunters. Phoenix House, London, 229 pp.

Lindroth, C.H. 1957. The Faunal Connections between Europe and North America. Wiley, New York, 344 pp.

Lodge, D.M. 1993. Biological invasions: lessons for ecology. Trends in Ecology and Evolution 8:133–137.

Mack, R.N., D. Simberloff, W.M. Lonsdale, H. Evans, M. Clout and F.A. Bazzaz. 2000. Biotic invasions: causes, epidemiology, global consequences, and control. Ecological Applications 10:689–710.

Marlatt, C.L. 1899. The laissez-faire philosophy applied to the insect problem. In: Proceedings of the Eleventh Annual Meeting of the Association of Economic Entomologists. U.S. Department of Entomology, Division of Entomology Bulletin 20, pp. 5–19.

Marlatt, C.L. 1911. Need of national control of imported nursery stock. Journal of Economic Entomology 4:107–126.

Marlatt, C.L. 1953. An Entomologist's Quest: the Story of the San Jose Scale; the Diary of a Trip Around the World–1901-1902. Monumental, Washington, DC, 338 pp.

Martin, P.S. 1973. The discovery of America: the first Americans may have swept the Western Hemisphere and decimated its fauna within 1000 years. Science 179:969–974.

Mattson, W.J., P. Niemelä, I. Millers and Y. Inguanzo. 1994. Immigrant phytophagous insects on woody plants in the United States and Canada: an annotated list. U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station General Technical Report NC–169, 27 pp.

McGregor, R.C. (Chairman). 1973. The emigrant pests: a report to Dr. Francis J. Mulhern, Administrator, Animal and Plant Health Inspection Service, Hyattsville, Maryland.

Metcalf, R.L. 1996. Applied entomology in the twenty-first century: needs and prospects. American Entomologist 42:216–227.

Myers, J.G. 1934. The arthropod fauna of a rice-ship, trading from Burma to the West Indies. Journal of Animal Ecology 3:146–149.

National Plant Board. 1999. Safeguarding American Plant Resources: a Stakeholder Review of the APHIS–PPQ Safeguarding System, 132 pp.

Niemelä, P. and W.J. Mattson. 1996. Invasion of North American forests by European phytophagous insects. BioScience 46:741–753.

Pierce, W.D. 1917. A Manual of Dangerous Insects Likely to be Introduced in the United States Through Importations. U.S. Government Printing Office, Washington, DC, 256 pp.

Pimentel, D., L. Lach, R. Zuniga and D. Morrison. 2000. Environmental and economic costs of nonindigenous species in the United States. BioScience 50:53–65.

Popham, W.L. and D.G. Hall. 1958. Insect eradication programs. Annual Review of Entomology 3:335–354.

Ross, H.H. 1953. On the origin and composition of the Nearctic insect fauna. Evolution 7:145–158.

Ruesink, J.L., I.M. Parker, M.J. Groom and P.M. Kareiva. 1995. Reducing the risks of nonindigenous species introductions: guilty until proven innocent. BioScience 45:456–477.

Sailer, R.I. 1978. Our immigrant fauna. Bulletin of the Entomological Society of America 24:3–11.

Sailer, R.I. 1983. History of insect introductions. In: Exotic Plant Pests and North American Agriculture, C.L. Wilson and C.L. Graham (eds.). Academic, New York, pp. 15–38.

Sanderson, E.D. 1906. National control of introduced insect pests. U.S. Department of Agriculture, Bureau of Entomology Bulletin 60: 95–104.

Sasscer, E.R. 1940. Undesirable insect aliens. Journal of Economic Entomology 33:1–8.

Sasscer, E.R. 1946. Report on the Special Survey for Insect Pests and Plant Diseases in the Vicinity of Ports of Entry. U.S. Department of Agriculture, Agricultural Research Administration, Bureau of Entomology and Plant Quarantine, Division of Foreign Plant Quarantines, 79 pp.

Shafland, P.L. and W.M. Lewis. 1984. Terminology associated with introduced organisms. Fisheries 9(4):17–18.

Smith, H.S. 1929. On some phases of preventive entomology. Scientific Monthly 29:179–184.

Soulé, M.E. 1990. The onslaught of alien species, and other challenges in the coming decades. Conservation Biology 4:233–239.

Surface, H.A. 1915. The annual report of the Bureau of Zoology of the Department of Agriculture. In: 20th Annual Report of the Pennsylvania Department of Agriculture, Harrisburg, 1914:78–99.

Swain, R.B. 1952. How insects gain entry. In: Insects: The Yearbook of Agriculture 1952, F.C. Bishopp (Chairman) et al. (eds.). U.S. Government Printing Office, Washington, DC, pp. 350–355.

Symons, T.B. 1911. A practical method of inspecting imported seedlings. Journal of Economic Entomology 4:263–265.

Turnbull, A.L. 1967. Population dynamics of exotic insects. Bulletin of the Entomological Society of America 13:333–337.

Turnbull, A.L. 1979. Recent changes to the insect fauna of Canada. In: Canada and Its Insect Fauna, H.V. Danks (ed.). Memoirs of the Entomological Society of Canada 108:180–194.

Turnbull, A.L. 1980. Man and insects: the influence of human settlement on the insect fauna of Canada. Canadian Entomologist 112:1177–1184.

U.S. Congress, Office of Technology Assessment. 1993. Harmful Non-indigenous Species in the United States (OTA–F–565). U.S. Government Printing Office, Washington, DC, 391 pp.

U.S. Department of Agriculture, Agricultural Research Service. 1960. Plant Pest Detection. ARS Special Report (22–63). Agricultural Research Service, U.S. Department of Agriculture, Washington, DC, 8 pp.

Van Driesche, J. and R. Van Driesche. 2000. Nature Out of Place: Biological Invasions in the Global Age. Island Press, Washington, DC, 363 pp.

Vitousek, P.M., C.M. D'Antonio, L.L. Loope and R. Westbrooks. 1996. Biological invasions as environmental change. American Scientist 84:468–478.

Webster, F.M. 1892. Early published references to some of our injurious insects. Insect Life 4:262–265; Part II, 4:323–326.

Wheeler, A.G., Jr. and T.J. Henry. 1992. A Synthesis of the Holarctic Miridae (Heteroptera): Distribution, Biology, and Origin, with Emphasis on North America. Thomas Say Foundation Monograph 15. Entomological Society of America, Lanham, Maryland, 282 pp.

Wheeler, A.G., Jr. and H.F. Nixon. 1979. Insect survey and detection in state departments of agriculture. Special Publication. Pennsylvania Department of Agriculture, Harrisburg, 28 pp.

Whitehead, D.R. and A.G. Wheeler, Jr. 1990. What is an immigrant arthropod? Annals of the Entomological Society of America 83:9–14.

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.

Wilson, E.O. 1992. The Diversity of Life. Harvard University Press, Cambridge, 424 pp.

Use of Semiochemicals for Survey and Detection of Exotic Insects: Principles and Constraints

Ring T. Cardé
Department of Entomology
University of California
Riverside, CA 92521

Abstract

This review concentrates on the principles of surveying for exotic invaders with semiochemical-baited traps and examines three possible strategies for improving detection of exotic insects. 1) What constrains the development of traps having an extended range of attraction? 2) Is the trap's detection sensitivity influenced by the failure of some insects attracted to a trap to be captured? 3) What empirical and simulation techniques can be used to enhance our understanding of the meaning zero trap catch and to optimize spatial patterns of deployment? Selected evidence from a variety of survey and detection cases is considered, but examples relate mainly to survey methods used to detect the spread and invasion of the gypsy moth (*Lymantria dispar*), which is a species of special interest. It is concluded that improvements in the technology of trapping are attainable with simple behavioral assays. Such improvements should lower the cost of surveys and enhance their reliability. Correlation of negative trap catch with the probability of missing an incipient infestation remains at the heart of survey interpretation. Mark-recapture protocols and simulation modeling are two techniques that should prove useful for improving patterns of trap deployment and interpretation of survey results

Introduction

Semiochemical-baited traps are widely used for monitoring of insect movement and detection of invasive species. Such traps release odorants mediating flight towards a wide variety of resources, including attraction to a mate, to sources of adult food, or to an oviposition site. Many kinds of survey traps are baited with sex-attractant pheromones; when pheromone-baited traps are deployed in a grid, they often are capable of detecting populations at very low density. Traps baited with lures based on odors used in detecting adult food also have proven crucial to some survey programs that attempt to detect a spectrum of true fruit fly species with a single type of trap. Other monitoring programs for tree-infesting beetles have relied on traps baited with host odor such as alpha-pinene or ethanol. Such non-specific lures may sample insect populations only in the immediate vicinity of the trap. In a few cases, the behavioral and ecological *raison d'être* for attraction to a compound remains enigmatic. For example, for 85 years male Mediterranean fruit flies, *Ceratitis capitata*, have been known to be attracted to methyleugenol (called "medlure"). One possible explanation for the attractive properties of medlure and the related compound trimedlure is that both stimulate aggregation (lekking) behavior of males as a prelude to attraction of females and mating. These two compounds, however, are not released by males, nor do they seem to be released by plants on which natural aggregations occur in the field (Cunningham, 1989). There are also many trapping systems based on insect attraction to traps that mimic only the visual features of a resource. For example, the attraction of many phytophagous insects to yellow panels (typically with a peak reflectance of light near 550 nm) relies on this hue mimicking the peak wavelength of reflectance from green leaves. These selected examples illustrate that trap-based survey and detection programs rely on a spectrum of insect responses to resources.

The probability of detecting of an incipient population is highly correlated to the density of traps, and the cost of deploying a survey grid rises with density of traps set out. There would appear to be two seemingly straightforward ways to improve the sensitivity of survey traps: first, enhance the "range" of a trap by luring insects over greater distances, or, second, capture a greater proportion of insects arriving at the immediate vicinity of the trap. Regardless of the traps' range and efficiency of capture, interpretation of trap catch is a fundamental problem. For example, interpretation of zero catch in a grid of survey traps remains problematic: What is the probability that the survey has failed to detect a population? Conversely, when one or more adults are recovered from a trap, it can be difficult to determine from where the trapped individuals originate.

This review will emphasize the principles of surveying for exotic invaders with semiochemical-baited traps and examine three possible strategies for improving detection of exotic insects. First, what constrains the development of traps having an extended range of attraction? Second, is the trap's detection sensitivity influenced by the failure of some insects attracted to a trap to be captured? These two issues are related to how a plume of semiochemical diffuses in wind and how the target insect reacts to this dispersion pattern and instantaneous wind direction. A third consideration is what empirical and simulation techniques can be used to enhance our understanding of the meaning zero trap catch and to optimize spatial patterns of deployment?

To explore these issues, selected evidence from a variety of survey and detection cases will be considered, but a principal example will be survey methods to detect the spread and invasion of the gypsy moth (*Lymantria dispar*). This species is of special interest because established populations, now ranging from throughout the northeastern United States south to the Carolinas and to the upper Midwest, have the potential to invade much of the remaining United States, and there is an active management program (STS or Slow the Spread) to retard its range expansion. Also, there is an occasional introduction of the Asian strain of the gypsy moth, usually to the west coast of North America via commercial shipping from the Russian Far East. The Asian strain is of special concern because, unlike its established North American counterpart, the female is capable of flight, and, therefore, the potential for rapid range expansion is greater than with the North America strain. Gypsy moth invasion is detected by capture of males in traps baited with (+)-disparlure, the female-emitted pheromone. The number of gypsy moth traps deployed in the United States by state agencies in cooperation with APHIS and the Forest Service is remarkable: 300,000 to 350,000 yearly. The cost to procure, set and retrieve an individual survey trap varies with the density of placement, terrain, and to some extent how an agency calculates costs: cost per trap ranged between $18 and $80. In 2000, APHIS estimated the expenses for monitoring of the Asian and European strains at $5,735,671. The cost of traps used in the Slow the Spread (STS) Program was $4,490,000, for a combined total of $10,225,671 (V.C. Mastro, APHIS, PPQ, personal communication).

Meteorological and Behavioral Factors Influencing Trapping Range

Patterns of pheromone dispersion. Turbulent diffusion is the dominant process influencing the structure of odor plumes as they are transported downwind (Murlis et al., 1992). Molecular diffusion in contrast has relatively little effect on the plume dispersion because its scale of movement (ca. 2 mm s^{-1}) is comparatively small. Turbulence causes an initially small emission of odorant to expand into a plume comprised of odor filaments interspersed with pockets of "clean" air (Figure 1). When an odor is sampled at a fixed position downwind, it appears as a series of bursts interspersed with gaps of "clean" air (Murlis et al., 2000). When the signal is present, it fluctuates continually in intensity. The absence of the signal over large fractions of a second or longer intervals of time becomes more prevalent as the distance away from the odorant source increases. As the plume is carried downwind and expands, the average concentration of odor within the plume's boundaries declines. Moment-to-moment contact with individual filaments of odorant seems to govern the insect's upwind heading and velocity, at least among moths (Mafra-Neto & Cardé, 1994; Vickers & Baker, 1994).

Many meters away from the odor's source, some filaments still harbor relatively high concentrations of odor, suggesting that insects should detect odorant

Figure 1. *View from above of a 2-D representation of the instantaneous, above-threshold concentration of semiochemical from a point source dispersed in wind. The plume's origin is from the top and the plume's meandering path is caused by changes in the wind's velocity and direction. The arrows indicate instantaneous wind direction. An organism attempting to locate the source of the odorant by flying upwind while within the plume frequently would encounter gaps of "clean" air and an upwind trajectory often would take the responder beyond the plume's boundaries.*

from a trap at substantial distances downwind. Experimental evidence for such behavioral capabilities in insects is limited but persuasive. Individually caged male gypsy moths show by a wing-fanning response that they can readily detect a plume of synthetic pheromone in a forest at least 120 m downwind of its source (Elkinton et al., 1987). Presence of an odorant in an above-threshold concentration, however, does not signify that there is sufficient information available for a male moth to routinely navigate a course to the plume's origin. When gypsy moth males detecting pheromone (as evidenced by wing fanning) were released at distances up to 120 m downwind of the pheromone source, fewer than 10% of the males eventually reached the pheromone source (Elkinton et al., 1987). Those males that located the source did so with a mean transit time of 9 minutes. Had their flight been continuous and directly along the plume, males should have reached the source within several minutes, given their observed average net velocity of ca. 0.5 m s^{-1} flying along pheromone plumes in the field (Willis et al., 1994). The first problem is that turbulence causes the plume to be discontinuous (Figure 1), with the consequence that a male flying along the plume will encounter patches within the plume where pheromone is not detected. If the gap in the detection of odor is about a second or longer, progress toward the source ceases (Kuenen & Cardé, 1994). The second issue is that changes in wind direction and velocity cause the plume to meander, with the instantaneous direction upwind being aligned only infrequently with the plume's long axis (Figure 1) (Elkinton et al., 1987; Brady et al., 1989).

Orientation to plumes from distant odor sources. Progress upwind with the plume is mediated by optomotor anemotaxis (reviews: Baker, 1990; Arbas et al., 1993; Cardé, 1996). The only mechanism by which airborne organisms can detect the direction of wind flow while airborne is to apprise visually how wind has altered their flight path. In brief, this mechanism uses the flow of the insect's visual surround to determine its direction of movement with respect to the wind. If the flow of the visual field beneath the insect is front-to-back, then the insect is aligned with the wind. Upwind-versus downwind direction could be set by comparing the rate of its perception of longitudinal flow and either thrust or mechanosensory information. If the flow of the visual field has a transverse (to-the-side) component, then the insect can gauge that its trajectory is not directly upwind and redirect its course. Optomotor anemotaxis has been verified experimentally using wind tunnel assays in several moth families and in *Drosophila* flies (David, 1982) and *Aedes* mosquitoes (Kennedy, 1940).

A second mechanism to achieve upwind displacement is "aim-and-shoot." In this maneuver, the insect simply uses mechanoreceptors to detect the upwind direction before take-off. The direction of the ensuing flight path is maintained by following a visual course aimed towards the previously sensed upwind direction. If contact with odor is lost, then landing ensues; if odorant is encountered again, flight resumes. Because of the plume's fragmented nature and discontinuities between the wind direction and the plume's long axis, progress towards the odor source over distances of many meters would occur as a series of "steps" of intermittent flights and landings. Evidence for the aim-and-shoot maneuver comes mainly from onion maggot flies (Dindonis & Miller, 1980), cabbage root flies (Finch & Skinner, 1982) and tsetse flies (Bursell, 1987; Brady et al., 1990). It is important to recognize that many, if not all, of the insects employing the aim-and-shoot maneuver may switch while in flight to conventional optomotor anemotaxis. The optomotor reaction might be engaged either when wind is of sufficient magnitude to supply unambiguous directional information, or when the course set by aim-and-shoot maneuver and the upwind direction gauged by the optomotor response are in conflict. The precise wind velocities influencing the presumed shuttle between these two maneuvers remain to be determined, but such a redundancy in orientation strategies would seem to be an advantageous way to cope with either wind speeds or light levels that might be insufficient for the optomotor reaction.

Significance of plume structure and orientation mechanisms to the effective range of a semiochemical lure. Because of the fragmented distribution of odor within the plume, an insect heading upwind within the plume's boundaries frequently will encounter patches of odorant-free air, especially well downwind of the odorant's source where signal intermittency is high (Figure 1). When such gaps in odorant are encountered, upwind movement ceases. Further progress towards the source of the odorant requires a strategy for re-contacting the odorant. An insect may either "cast" (side-to-side-sweeps without upwind progress) (Keuenen & Cardé, 1994) or loop downwind (Kerguelen & Cardé, 1997). If the odorant is re-contacted, then upwind flight can resume. The frequent misalignment of the upwind direction with the plume's long axis (Figure 1) means that an insect flying upwind within the odor plume often will exit the plume, but the strategies of casting or looping will facilitate plume re-entry.

The plume's patchy internal structure and the misalignment of the instantaneous wind direction with the plume's long axis both dictate that gypsy moth males could not routinely (or quickly) navigate a course to a pheromone source located quite some distance upwind, despite their ability to detect the presence of the pheromone (Elkinton et al., 1987). Female gypsy moths, communicating their availability and their upwind location by release of pheromone, face the same meteorological constraints to extending of their distance of communication as those that limit the range of pheromone-baited traps. Increasing the rate of pheromone release will not appreciably increase the probability of females or traps luring a moth, even though the detectable threshold will extend farther downwind. (A parallel situation exists for males; males that are more sensitive to pheromone – that is those having a lower threshold of response – would be able to detect a plume at increased distances away from the female, but their ability to find the female would remain constrained by the characteristics of a patchy plume and the misalignment of wind direction and the plume's long axis.) The limitations of plume fragmentation and instantaneous wind direction are applicable to all organisms orienting upwind to point sources of odorant. Therefore, attempts to devise detection traps that are more sensitive by increasing the rate of lure emission face meteorological limitations.

Meteorological and Behavioral Factors Influencing Capture in Traps

Measuring efficiency of trap capture. Leaving aside the issues of long-distance orientation, what is the probability of an insect being captured after it has arrived at the vicinity of the trap? There are relatively few quantitative studies bearing on this issue, but those that are available suggest that trapping efficacy varies widely. Lewis and Macaulay (1976) compared the catch of six types of pheromone trap baited identically for the pea moth, *Cydia nigricana*. The magnitude of catch varied by a factor of 10, and direct behavioral observations of males showed that the efficiency of capture of males arriving within 2 cm of the trap varied from 12 to 48%. Some of these differences seemed to be explained by differences in the retentive properties of sticky traps and by the area of the trapping surface. Another important factor (considered explicitly in a following section) was the characteristics of the pheromone plume emanating from the trap.

Phillips and Wyatt (1992) advocated direct behavioral observations for determining how permutations of trap design alter trap catch. By simply varying the angle of entrance ramps to two types of sticky trap baited with food odor, catch of cockroaches was altered by a factor of about two. But the way in which catch was altered varied with ramp angle: few insects entered a trap with 60° angle ramp, but none escaped. All insects entered the 0° angle ramp, but half escaped. Such observations can guide improvements in trap design.

Elkinton and Childs (1983) compared the efficiency (the proportion of those males approaching the trap that is captured) for the gypsy moth of two trap types. Both types were baited with pheromone, (+)-disparlure. The "milk-carton trap," a trap with eight moth-sized entry ports, two on each side of the trap, was compared with the sticky wing trap. The milk carton trap is widely used in areas where gypsy moths are established because it has a collection capacity of hundreds of males, and its efficiency is not altered by the presence of males in the trap, except in the usual circumstance that there are so many males in the trap that their decomposition produces repellent odors (Elkinton, 1987). In contrast, the sticky surface of a wing trap is much less able to retain males once its retentive surfaces become paved with males and wing scales. Its efficiency therefore declines precipitously as males are captured.

The wing trap is similar in trapping principle to the sticky Delta trap now used for detection of gypsy moths in non-infested areas or for delimitation surveys of newly found, very low density invasions. In practice, the comparatively simple Delta trap should be ideal for survey and delimitation (provided its information is interpreted correctly) because, from a management perspective, presence of males versus their absence is the most salient information, provided that this information can be interpreted correctly. The capture of a single male signifies the need for a follow-up delimitation survey. The presence of several males is sufficient information for the manager to assume the presence of a nearby breeding population.

Elkinton and Childs (1983) found that milk-carton traps captured 10% of gypsy moth males approaching within 2 m of the trap and 44% of males contacting the trap; for fresh wing traps the proportions were 20 and 76%, respectively. Males that were not captured were observed to leave the test area, although one cannot be certain that they did not subsequently reorient to the trap. Assuming that the Delta traps and wing traps have similar trapping efficiencies, the relevance of such observations is quite apparent: if the trap could be modified to be more efficient, the sensitivity of the survey system should be enhanced, although by what factor cannot be inferred. Males that are not captured and depart from the vicinity of the trap may be subject to mortality or they may disperse beyond the effective range of the trap.

Evidence from mark-release-recapture trials with the gypsy moth (Elkinton & Cardé, 1980) suggests that the daily mortality plus emigration from the trap grid of males in a Michigan forest was 96%. When gypsy moth males fly in the absence of pheromone (ranging flight in "search" of a female), their trajectories appear to be random with respect to the direction of the wind (Elkinton & Cardé, 1983). Therefore, males that have not been captured on a given encounter with a trap may never be captured because of mortality or dispersal.

Effect of rate of semiochemical emission on capture efficiency. The effect of the rate of semiochemical emission has so far been considered for its effect on the extent of the downwind projection of the active space. Orientation of insects close to the odor source and, therefore, their capture in traps also are affected by the rate of emission. Some moths such as the oriental fruit moth (*Grapholita molesta*) are particularly attuned to a narrow band of emission rates (Baker & Cardé, 1979), which are close to the natural rate of female emission (Baker et al., 1980). Higher rates of emission diminish or eliminate trap catch (Figure 2) because of an antagonist effect on close-range orientation behaviors (Baker & Cardé, 1979). For other species such as the gypsy moth, trap catch and rate of pheromone are positively correlated (Figure 2), although trap catch may plateau at high emission rates (Cardé et al., 1977; Plimmer et al., 1977). Even in such cases where trap catch increases with rate of emission, it is not certain that higher rates of emission do not negatively affect orientation at close range, causing a proportion of males to veer away from the trap before capture. Consequently, it would be possible to use a high emission rate to lure more insects to the trap's vicinity while simultaneously lowering the probability of capture by the trap.

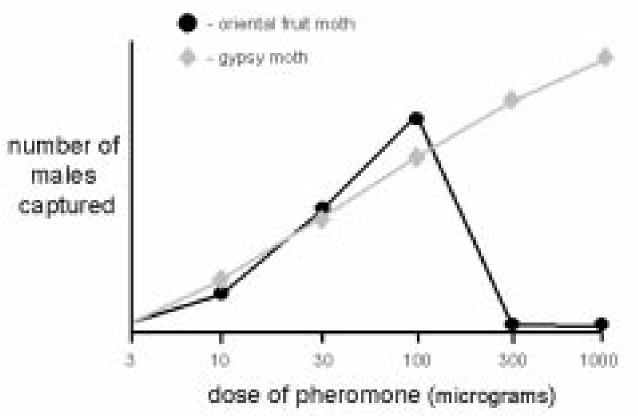

Figure 2. *Effect of dose of pheromone in the dispenser on trap capture. For the oriental fruit moth (*Grapholita molesta*), capture peaks near 100 µg and declines sharply at higher doses (Baker & Cardé, 1979). For the gypsy moth (*Lymantria dispar*), trap capture increases gradually and reaches a plateau at the highest doses (Cardé et al., 1977; Plimmer et al., 1977).*

Effect of fine-scale plume structure on capture efficiency. Orientation of male moths along pheromone plumes is governed, in part, by the fine-scale distribution of pheromone. Although definitive evidence is so far limited to several species, in those moths studied, encountering filaments at rates near 10 Hz causes a flight aimed more directly upwind accompanied by an increase in velocity (Mafra-Neto & Cardé, 1994; Vickers & Baker, 1994). Filaments of pheromone encountered at rates near 5 Hz or less tend to produce zigzag courses with little upwind displacement. Filaments with rates much below 5 Hz evoke casting or fail to promote sustained orientation.

The spatial features of the plume emanating from a trap also should affect trap capture, as first demonstrated by Lewis and Macaulay (1976) with the pea moth, *Cydia nigricana*. They documented characteristics of the plumes from six trap types with visible "smoke" tracers. The differences in the numbers of males lured to traps and those eventually captured were attributed in part to the boundaries, length and internal turbulent structure of the plumes. The same explanation likely applies to the differences among trap types in efficiency of catch of male gypsy moths, as documented by Elkinton and Childs (1983).

These case studies illustrate that altering trap design could produce substantial improvements in trapping efficiency. Such improvements might be accomplished by empirical field tests of design versus magnitude of catch, or, more usefully, by direct measurements of efficiency of capture in the field (Lewis & Macaulay, 1976; Elkinton & Childs, 1983) or in the wind tunnel (Foster & Muggleston, 1993). Another approach would be to characterize the fine-scale features of plumes released from traps by using a surrogate odor that can be readily measured. Propylene is a useful surrogate odor, and its density can be measured at high sampling rates with a photoionization detector (Justus & Cardé, 2002). So far we have less information on the close-range efficiency of traps used for true fruit flies, despite the extensive efforts underway to survey for their entry into the United States. Even a modest improvement in trapping efficiency might enhance their usefulness in detection.

Interpretation of Trap Catch

Empirical methods. There is extensive literature on the use of mark-release-recapture to establish the presumptive "attractive range" of semiochemical-baited traps. What such experiments generally have measured is the probability of capture of cohorts of insects released at various distances away from a single trap. In some procedures, insects are released in the presumptive downwind direction and in other protocols in a circular pattern surrounding the trap. It is generally not feasible to release insects while they are enveloped by a plume of semiochemical (but see the methods of Linn et al., 1986; Elkinton et al., 1987; Brady et al., 1989). Thus, in such range-of-attraction experiments, the distance over which an insect travels to a trap is a compounding of a) its survival and dispersal before entering the plume of semiochemical with b) its ability to find and enter the trap. The dispersal behavior and survival of an insect prior to its capture may well contribute more to the apparent range of the trap than the insect's ability to detect and follow a plume into the trap. From the perspective of interpretation of survey data, however, what remains relevant is the probability of capture at varying distances of initial dispersion from the trap.

A second general method for studying the range of influence of a trap involves the releases of insects into a grid of traps (Elkinton & Cardé, 1980). If the experimental grid has a very close placement of traps (on the order of 100 m spacing), then insects are released at points located in the middle of each square of four traps. This pattern produces release sites that are situated at a distance from the four surrounding traps that is 70% of the intertrap distance. If the intertrap distance is comparable to the spacing used in most surveys (on the order of 800 m or more), then insects are released evenly at as many sites in the area between the traps as operationally practicable. This method has the advantage of mimicking the recapture conditions encountered by insects that are evenly dispersed in survey grids. With this methodology, capture of male gypsy moths in 800 by 800 m (½ by ½ mile) grids was calibrated to show that 4% of the released males were captured. Information from an 80 by 80 m grid was used to verify that one major factor explaining the low proportion recaptured was the low day-to-day survival of males.

Simulation modeling. As valuable as mark-release-recapture methods are for developing an understanding of the meaning of positive and negative trap catch, such methods are very difficult to use in exploration of how differences in trap design, rate of semiochemical release, and trap placement alter probability of detection in surveys. Simulation modeling permits the systematic manipulation of various factors contributing to trap catch: the wind conditions dictating plume dispersal, general features of weather such as temperature, the rate of semiochemical release, trap density, and assumptions about insect dispersal and orientation behavior. For modeling to provide a reasonable simulation of the dispersion of plumes and insect behavior, it requires that we reproduce the physical features of the odorant plume in appropriate habitats and understand the particular insect dispersal and orientation strategies of the target species.

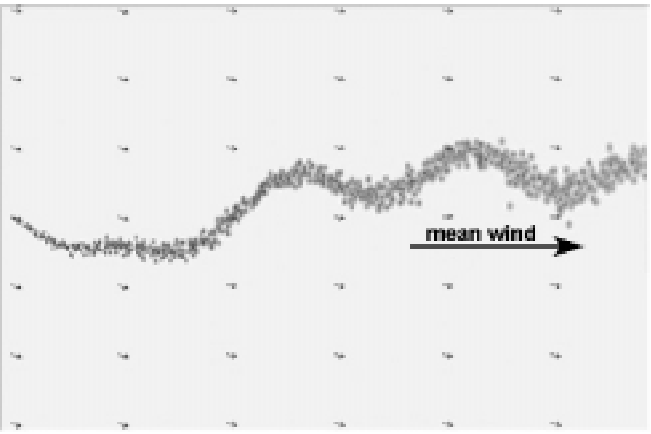

Figure 3. *A simulation model of plume dispersion with a moderate level of meander (i.e. wind direction and velocity are relatively unvarying). Arrows depict instantaneous wind directions The dark areas indicate an above-threshold concentration of pheromone. The rate of pheromone emission and the threshold of response were set to match those of the gypsy moth (*Lymantria dispar*). The area represents a 60 by 100 m field (see Li et al., 2002).*

Of course, models assume some compromises in simulation of the complexities of plume dispersion, and in behavior of insects in finding and navigating along a plume. To be computationally feasible, for example, the Li et al. (2002) model of plume dispersion and insect odor-location strategies operates in a planar world set at the height of the odorant source (Figure 3). The model neglects computation of the plume's vertical diffusion and possible vertical movement of the responding insect. This simplification is not entirely unreasonable in that many kinds of insects fly at relatively set heights above the ground, typically at heights that make contact with a plume from a natural source likely. Plumes do, however, disperse to some extent vertically, especially under some unstable (adiabatic) atmospheric conditions typical of midday (Fares et al., 1980), but also at night (Schal, 1982). Nonetheless, simulation modeling allows estimates of how improvements in trap range or efficiency of a trap might enhance detection protocols.

Future Directions

Semiochemical-based traps are widely used as sentinels for the arrival of many kinds of exotic invaders. Once such an invasion is detected, then such traps typically serve as the basis of a subsequent delimitation survey in which a grid of closely spaced traps is used to define the probable boundaries of an incipient population. Such demographic information can be helpful to the selection of a particular eradication strategy. Methods for design of survey traps generally have been to modify the trap's configuration by-trial-and-error and to vary the lure's emission rate, with the goal of producing the highest possible trap catch. The tacit assumption is that the trap design and lure giving the highest catch is an optimum combination for detection. The trap's efficiency of capture, which might be quite low, remains unknown with such approaches.

Research determining how the spatial pattern of trap catch in surveys relates to natural patterns of distribution and density relies largely on mark-release-recapture experiments. The validity of such protocols rests largely on the assumption that the released and introduced insects have comparable dispersal behaviors and abilities to find a lure-baited trap. In the case of Mediterranean fruit flies, some laboratory-reared flies do not appear comparable in semiochemical response to wild flies (Cayol, 1999), although, of late, the "competitiveness" of these flies has been improved. Despite these limitations, mark-release-recapture experiments nonetheless provide crucial information on how trap catch relates to natural densities.

A simulation modeling approach can generate information that would be difficult if not impossible to obtain through either behavioral observations or mark-release-recapture. Models allow for the systematic manipulation of changes in environmental conditions, trap range, capture efficiency, trap density and insect distribution, to see how changes in these parameters could alter the outcome of a survey. Estimates of the probability of detecting or missing various low-level populations can be based on many simulation runs of a given set of conditions rather than on the outcome of a single or several expensive field experiments.

Conclusions

Improvements in the technology of trapping are attainable with simple behavioral assays. Such improvements should lower the cost of surveys and enhance their reliability. Correlation of negative trap catch with the probability of missing an incipient infestation remains at the heart of survey interpretation. Mark-recapture protocols and simulation modeling are two techniques that should prove useful for improving patterns of trap deployment and interpretation of survey results.

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References

Arbas, E.A., M.A. Willis and R. Kanzaki. 1993. Organization of goal-orientated locomotion: pheromone-modulated flight behavior of moths. In: Biological Neural Networks in Invertebrate Neuroethology and Robotics, R.D. Beer, R.E. Ritzmann and T. McKenna (eds.). Academic Press, San Diego, pp. 159–188.

Baker, T.C. 1990. Upwind and casting flight: complementary phasic and tonic systems used for location of pheromone sources by male moths. In: Proceedings of the X International Symposium on Olfaction and Taste, Oslo, pp.18–25.

Baker, T.C. and R.T. Cardé. 1979. Analysis of pheromone-mediated behavior in male *Grapholitha molesta*, the oriental fruit moth (Lepidoptera: Tortricidae). Environmental Entomology 8:956–968.

Baker, T.C., R.T. Cardé and J.R. Miller. 1980. Oriental fruit moth pheromone component release rates measured after collection by glass surface adsorption. Journal of Chemical Ecology 6:749–758.

Brady, J., G. Gibson and M.J. Packer. 1989. Odour movement, wind direction, and the problem of host-finding by tsetse flies. Physiological Entomology 14:369–380.

Brady, J., M.J. Packer and G. Gibson. 1990. Odour plume shape and host finding by tsetse. Insect Science and its Application 5:345–349.

Bursell, E. 1987. The effect of wind-borne odours on the direction of flight in tsetse flies, *Glossina* spp. Physiological Entomology 12:149–156.

Cardé, R.T. 1996. Odour plumes and odour-mediated flight in insects. In: Olfaction in Mosquito–Host Interactions, G.R. Bock and G. Cardew (eds.). CIBA Foundation Symposium 200, John Wiley & Sons, Chichester, U.K., pp. 54–70.

Cardé, R.T., C.C. Doane, T.C. Baker, S. Iwaki and S. Marumo. 1977. Attractancy of optically active pheromone for male gypsy moths. Environmental Entomology 6:768–772.

Cayol, J.-P. 1999. Changes in sexual behavior and life history traits of tephritid species caused by mass-rearing processes. In: Fruit Flies (Tephritidae): Phylogeny and Evolution of Behavior, M. Aluja and A.L. Norrbom (eds.). CRC Press, Boca Raton, Florida, pp. 843–860.

Cunningham, R.T. 1989. Parapheromones. In: Fruit Flies. Their Biology, Natural Enemies and Control, Vol. 3A, A.S. Robinson and G. Hooper (eds.). World Crop Pests, Elsevier, Amsterdam, pp. 231–230.

David, C.T. 1982. Competition between fixed and moving stripes in control of orientation by flying *Drosophila*. Physiological Entomology 7:151–156.

Dindonis, L.L. and J.R. Miller. 1980. Host-finding behavior of onion flies, *Hylemya antiqua*. Environmental Entomology 9:769–772.

Elkinton, J.S. 1987. Changes in efficiency of the pheromone-baited milk-carton trap as it fills with male gypsy moths (Lepidoptera: Lymantriidae). Journal of Economic Entomology 80:754–757.

Elkinton, J.S. and R.T. Cardé. 1980. Distribution, dispersal and apparent survival of male gypsy moths as determined by capture in pheromone-baited traps. Environmental Entomology 9:729–737.

Elkinton, J.S. and R.T. Cardé. 1983. Appetitive flight behavior of male gypsy moths (Lepidoptera: Lymantriidae). Environmental Entomology 12:1702–1707.

Elkinton, J.S. and R.D. Childs. 1983. Efficiency of two gypsy moth (Lepidoptera: Lymantriidae) pheromone-baited traps. Environmental Entomology 12:1519–1525.

Elkinton, J.S., C. Schal, T. Ono and R.T. Cardé. 1987. Pheromone puff trajectory and upwind flight of male gypsy moths in a forest. Physiological Entomology 12:399–406.

Fares, Y., P.J.H. Sharpe and C.E. Magnuson. 1980. Pheromone dispersion in forests. Journal of Theoretical Biology 84:335–359.

Finch, S. and G. Skinner. 1982. Upwind flight by the cabbage root fly, *Delia radicum*. Physiological Entomology 7:387–399.

Foster, S.P. and S.J. Muggleston. 1993. Effect of design of a sex-pheromone baited trap on behavior and catch of male *Epiphyas postvittana* (Walker). Journal of Chemical Ecology 19:2617–2633.

Justus, K.A. and R.T. Cardé. 2002. Flight behaviour of male almond and pink bollworm moths in homogeneous clouds of pheromone. Physiological Entomology (*in press*).

Kennedy, J.S. 1940. The visual responses of flying mosquitoes. Proceedings of the Zoological Society of London A, 109:221–242.

Kerguelen, V. and R.T. Cardé. 1997. Manoeuvres of female *Brachymeria intermedia* flying towards host-related odours in a wind tunnel. Physiological Entomology 22:344–356.

Kuenen, L.P.S. and R.T. Cardé. 1994. Strategies for recontacting a lost pheromone plume: casting and upwind flight in the male gypsy moth. Physiological Entomology 19:15–29.

Lewis, T. and E.D.M. Macaulay. 1976. Design and elevation of sex pheromone traps for pea moth, *Cydia nigricana* (Steph.) and the effect of plume shape on catches. Ecological Entomology 1:175–187.

Li, W., J. Farrell and R.T. Cardé. 2002. Tracking of fluid-advected odor plumes: strategies based on insect behaviors. Adoptive Behavior (in press).

Linn, C.E., Jr., M.G. Campbell and W.L. Roelofs. 1986. Pheromone components and active spaces: what do moths smell and when do they smell it? Science 237:650–652.

Mafra-Neto, A. and R.T. Cardé. 1994. Fine-scale structure of pheromone plumes modulates upwind orientation of flying moths. Nature 369:142–144.

Murlis, J., J.S. Elkinton and R.T. Cardé. 1992. Odor plumes and how insects use them. Annual Review of Entomology 37:505–532.

Murlis, J., M.A. Willis and R.T. Cardé. 2000. Spatial and temporal structures of pheromone plumes in fields and forests. Physiological Entomology 25:211–222.

Phillips, A.D.G. and T.D. Wyatt. 1992. Beyond origami: using behavioural observations as a strategy to improve trap design. Entomologia experimentalis et applicata 62:67-74.

Plimmer, J.R., C.P. Schwalbe, E.C. Paszek, B.A. Bierl, R.E. Webb, S. Marumo and S. Iwaki. 1997. Contrasting effectiveness of (+) and (–) enantiomers of disparlure for trapping native populations of gypsy moth in Massachusetts. Environmental Entomology 6:518–522.

Schal, C. 1982. Intraspecific vertical stratification as a mate-finding mechanism in tropical cockroaches. Science 215:1405–1407.

Vickers, N.J. and T.C. Baker. 1994. Reiterative responses to single strands of odor promote sustained upwind flight and odor source location by moths. Proceedings of the National Academy of Sciences, U.S.A. 91:5756–5670.

Willis, M.A., C.T. David, J. Murlis and R.T. Cardé. 1994. Effects of pheromone plume structure and visual stimuli on the pheromone-modulated upwind flight of male gypsy moths (*Lymantria dispar* L.) in a forest. Journal of Insect Behavior 7:385–409.

Using Plant Traits to Guide Detection Efforts

Sarah Reichard
Research Assistant Professor
University of Washington

Abstract

Invasions may be divided into three phases: introduction, establishment, and impact on native species and environments. Because of a thriving and productive horticulture industry in most developed countries, as well as an increase in the use of plants for medicinal purposes, it is likely that a significant portion of the world' s plants may be intentionally introduced. The biology of a species, however, affects its ability to become established outside of cultivation. According to population biology theory, traits that increase the number of births and traits that decrease the number of deaths will allow a rapid increase in population size. Large populations are easier to detect, but usually much more difficult to control. Traits leading to increased birth include a short juvenile period, a lack of seed germination requirements, and large numbers of seeds produced. Traits that may decrease the death of individuals include regeneration from fragmented plant parts (such as following a disturbance) and traits relating to stress-tolerance, such as the ability to photosynthesize in stem tissues after leaf loss. These traits may be combined using various algorithms to gain the power to predict establishment. Impact, however, is an interaction of the attributes of a plant and the biotic and abiotic components of an ecosystem and is much more difficult to predict.

Introduction

Biological invasions are increasingly recognized as one of the most serious threats to the protection of biodiversity worldwide (Wilcove et al., 1998). Invasive non-native plants, while not posing the more obvious threat of non-native herbivores or pathogens, are capable of inflicting great harm on agricultural and natural systems. The impacts on native species range from competition for resources (e.g., Melgoza et al., 1990; Hester & Hobbs, 1992; Mesléard et al., 1993; Huenneke & Thomson, 1994), hybridization (Thompson, 1991), nitrogen fixation introduced or increased in natural areas (Vitousek et al., 1987), changed hydrologic cycles (Carman & Brotherson, 1982), increased sedimentation (Blackburn et al., 1982), and increased disturbance cycles (Bock & Bock, 1992; D'Antonio & Vitousek, 1992). A recent estimate put the economic cost of invasive plants in natural areas, agriculture, and gardens at $35 billion per year (Pimentel et al., 1999).

It has been estimated that there are approximately 260,000 vascular plant species in the world. To determine how many weed species we might have in the world, Eduardo Rapaport (1991) went through a useful exercise: if 10% of those species have the ability to colonize or develop weedy tendencies, that gives us 26,000 potential weed species. He estimated that there are currently 10,000 weed species now recognized, but he believes that only 4,000 of those species have actually been exchanged between regions of the world. The rest are natives in the areas in which they are considered weeds. That means that there are 22,000 potential weed species still available for exchange around the world. Even if this estimate is off by half, and even if only 10% of those species are capable of having a detrimental effect in natural areas, that means that 1,100 potentially serious weed species may still be introduced into the United States. Some of these may be tropical, but that would bring little comfort to those protecting natural areas in south Florida or Hawai'i.

Until recently, efforts to address the invasive species problem were directed mostly to control of existing problem species, with some efforts to prevent spread of those species through federal and state noxious weed laws. There has been a perception that invasions are completely case-specific and they, therefore, are not predictable *a priori*. However, by subdividing the invasion process into three stages and by looking at the factors facilitating those stages, some predictive power may be possible.

Prediction is the synthesis of past and present in an attempt to foretell the future (Saaty & Vargas, 1991). We predict something by relying on data of past happenings. The past and the present are irreversible and certain, but because facts of the past are largely incomplete, we must attempt to examine and interpret them.

This paper explores the current knowledge and possibilities of predicting invasions at three phases: introduction of the species, establishment of the species into self-reproducing populations, and the impact that invasive species can have on the invaded ecosystem.

Phase 1: Introduction

Invasive species may be introduced accidentally or intentionally. Accidental introduction includes the historical introduction through soil used as ships' ballast, contamination of commodities, and contamination of crop seed (U.S. Congress, 1993). Ships no longer use soil for ballast, and while seed crop contamination still occurs, it has been greatly reduced by the Federal Seed Act. Imported commodities are randomly sampled and inspected for contamination. While invasive plants are still accidentally introduced through these last two methods, laws have been passed and procedures are in place to reduce introduction along these pathways.

A significant number of species are introduced intentionally for horticulture, agriculture, or medicinal cures. Overall, about 65% of the plant species in the United States were likely introduced intentionally for horticulture (R. Mack, Washington State University, personal communication). A study found that nearly all of the woody species invading in the United States were introduced (at least in part) for horticulture or agriculture (Reichard, 1997). Horticulture is a thriving industry. The United States Department of Agriculture estimates that in 1997 (the last year for which there are figures) the floriculture and horticulture industry had cash receipts of $11.2 billion (USDA, 1999). Gardening is consistently listed as a top hobby in the U.S. Horticulture is an industry that is important to consumers, to improving the urban environment, and to the economy. Gardeners have a wide variety of tastes in plants, and plant explorers have been active in recent years (Meyer, 2000). Furthermore, the recent interest in herbal remedies has led to an increase in importation and farming of plants, many of which are known to have tendencies towards weediness (Reichard & White, *in press*).

The United States government puts few restrictions on the importation of plant species (see http://www.aphis.usda.gov/npb/safegard.html). The potential for future legal introductions for horticultural and other intentional purposes appears to be great. Potentially, we could expect just about any temperate or tropical plant species to be introduced into the United States.

Phase 2: Establishment

Changes in population size may be described by the basic population biology model of $N_{t+1} = N_t + B - D + I - E$ where N_t is the size of the population at a baseline time, B = births, D = deaths, I = immigration, and E = emigration. Thus, traits that increase the reproductive potential of a species and its ability to tolerate stress are going to be central to increase the size of a population. Traits that facilitate dispersal, such as light wind-dispersed seeds or animal-mediated dispersal will increase the probability of a species' spread outside the original source population. In order to understand what might cause the observed rapid increase of invasive plant populations, I have focused on measurable traits that might facilitate reproduction and stress-tolerance.

Methods

Species selection. North America. The North American research was conducted from 1991 to 1994. Woody plant species introduced into North America, north of the United States/Mexico border, prior to 1930 were included in this study, and this was done primarily by searching nursery and garden catalogs from 1930 and earlier. If a species was documented as invading non-agricultural systems through published sources, herbarium specimens, or communication with experts, it was considered to be an invasive species. A total of 235 species were included in this category, including 76 species that are considered to be true pest species with demonstrable impact to the invaded ecosystem. All listings that were clearly identifiable to species and were not considered to be invasive in the sources checked were categorized as non-invasive. Invasive species were defined as those that spread into native flora or managed plant systems, developed self-sustaining populations, and become dominant and/or disruptive to those systems.

Hawai'i. The work in Hawai'i was done in 1995 and 1996. Invasive plants were primarily determined by consulting the recent flora (Wagner et al., 1990). Those listed as invading outside cultivation were included, for a total of 181 species, 47 of which were considered pest species. These species were documented though examination of herbarium specimens at the Bishop Museum herbarium and through field observations. Non-invasive species were those listed as introduced prior to 1950 in a comprehensive garden plant book under development by the Bishop Museum in Honolulu. A total of 156 non-invasive species was identified.

Species traits and data analyses. Previous studies (e.g., Baker, 1965, 1974; Roy, 1990) have suggested some attributes that may contribute to invasive ability. These traits, when measurable, were included in the study. In addition, some traits were determined to have possible adaptive significance for invasive species and were included. Some traits were added to the Hawai'ian study because it was done after the North American work and additional traits were suggested. Also, because Hawai'i is a smaller geographic area, some field observations could be added.

Simple comparisons were done using t-tests for continuously recorded data (e.g., length of the juvenile period) and log-likelihood for non-continuous data (e.g., presence or absence of a trait). Because evaluating a table of data simultaneously may increase the chance of rejecting the null hypothesis when it is true, the sequential Bonferroni technique was used.

Discriminant analysis (DA) was used for both North America and Hawai'i and classification and regression trees (CART) for North America only. These techniques allowed me to identify combinations of traits that effectively divided invaders from non-invaders on the basis of traits. A full explanation of the methods may be found in Reichard and Hamilton (1997). Discriminant analysis finds linear combinations of traits, while CART breaks down the data set trait by trait to develop a dichotomously branching "tree" for decision-making (Brieman et al.,1984). In both cases, the model was developed on a randomly selected subset of species, then tested on the remaining species.

For North America, the results of the comparisons, DA and CART, were combined into a decision tree that evaluates invasive potential using several different predictive paths. The paths have three outcomes: accept (low risk of invasive establishment), reject (high risk of invasive establishment), and evaluate further (need more information and possible monitoring to place in accept or reject categories).

Results and Discussion

A number of probably adaptive traits were found to differ between invasive and non-invasive species, in some cases for both North American and Hawai'ian species, and in others, only one of the regions.

Plant traits. Because I was working with several hundred species over extensive geographic areas, I limited the traits studied to those that are easily identified. Thus, traits such as number of seeds produced per plant or genetic variation, traits that may influence invasive ability, were not considered. This also has the advantage that users of the results will not have to use vast information resources to duplicate the results.

The juvenile period is the time between the germination of the seed and the onset of flowering. A short juvenile period will allow a population to establish more rapidly. Herbert Baker (1974) theorized that the ideal weed would have rapid growth through the vegetative stage to reproduction. An estimated 22% of the natural area weeds in the United States are annuals and another 12% are biennials, which, by definition, have a short juvenile period. However, even the woody invasive species in North America have an average juvenile period of 4.0 ± 4.1 years, shorter than the 6.9 ± 8.1 years for non-invasive species ($p = 0.0001$). There appears to be a smaller difference in Hawai'i ($p = 0.02$), perhaps due to the year-round growing season that both invaders and non-invaders there have available. Woody invaders in Hawai'i had an average juvenile period of 3.5 ± 3 years and non-invaders 5.8 ± 7 years. When unknown, this trait may be estimated by its strong correlation to early rapid vegetative growth, or genome size apparently also correlated to short juvenile periods (Rejmánek, 1996) may be measured.

Vegetative reproduction is the spreading of plants by vegetative parts such as root suckers or soil layering of branches. It allows a population to spread when individuals are isolated and cannot be cross-pollinated. It may allow plants to recover from disturbance more quickly through the regeneration of plant parts. In North America, 44% of the invaders (53% of the pest species) vegetatively reproduce, while only 23% of the non-invaders do so ($p = 0.0001$). In Hawai'i, the difference is less significant ($p = 0.01$), with 23% of the invaders and 13% of the non-invaders reproducing this way. However, 36% of the invaders in Hawai'i are capable of coppicing, or regenerating from a cut stump, but only 8% of the non-invaders were ($p = 0.0001$). The North American study did not examine coppicing ability.

The seeds of many species require pretreatment for germination. Herbert Baker (1965) suggested that the ideal weed would have pregermination requirements that could be met in many environments. A comparison of weedy to less weedy *Echium* species found that the weedier species had more rapid seed germination (Forcella et al., 1986). In North America, 51% of the invasive species did not require any pretreatment, suggesting that they may be more flexible in requirements than the non-invaders, of whom only 30% needed no pretreatment ($p = 0.0001$). However, 44% of the non-invaders required a cold chilling period, while only 21% of the invaders needed it (p = 0.0001), suggesting that a need for precise requirements may be hampering invasive ability. In Hawai'i, there were no differences between invaders and non-invaders for germination requirements.

Seed size may affect dispersability and longevity of the seeds. In North America, there were no differences between invaders and non-invaders in seed size, but in Hawai'i the invasive species had an average size of 7.4 mm and the non-invaders 10.9 mm (p = 0.005). For a given amount of energy, more small seeds can be produced than large, increasing through volume the probability that some progeny will land in a spot favorable for germination (Stebbins, 1971). Invasive pine species also have been found to have smaller seeds than non-invasive species (Rejmánek & Richardson, 1996)

Many species have a symbiotic relationship with bacteria that convert atmospheric nitrogen to a form that may be absorbed by the plant. This may be particularly useful for species that invade disturbed areas because they are often low in nitrogen (Grubb, 1983). Nitrogen-fixation is strongly associated with the legume family, but several other families of invasive species, including the Casurinaceae, Eleagnaceae, Myrsinaceae, and others, also fix nitrogen. Although the total numbers are low, nitrogen fixation is more common in invaders in both North America (15% vs. 4%, p = 0.001) and Hawai'i (17% vs. 6%, p = 0.001).

Hybrids are generally sterile and thus, because there is no seed dispersed, less likely to become invasive. In North America, only 1% of the invasive species (and no pest species) were hybrids. They qualified as invasive because, once dispersed to an area, they spread vigorously by vegetative means. Non-invaders were 11% hybrids (p = 0.0001). In Hawai'i, 1% of the invaders were hybrids (no pest species), as were 5% of the non-invaders (p = 0.03).

Traits that did not differ. Several traits compared did not differ significantly, or were only slightly significant (losing significance when the Bonferroni correction was made). Those that differed only somewhat include: self-compatibility (pre-Bonferroni correction values, North America, p < 0.05, Hawai'i, p < 0.01); flowers agamospermic (North America, p < 0.01, Hawai'i, ns); biotic versus abiotic seed dispersal mechanisms (North America, p < 0.05, Hawai'i, ns), with more invasive species biotically dispersed; and leaves semi-evergreen (North America, p < 0.001, Hawai'i, ns). The following traits did not differ in any comparisons: plant form (tree, shrub, or vine), polyploidy or average chromosome numbers, fleshy versus dry fruits, average seed germination rate, reproductive systems, average seed longevity (studied in Hawai'i only), and most regions of origin.

Other Patterns

Biogeographic. Invades elsewhere. Probably the single best predictor of invasive ability is knowing what the species has done in other places where it has been introduced. It is a shorthand way of knowing that the species possesses traits that predispose it to establish outside of cultivation. It has been found useful for plants in Australia (Scott & Panetta, 1993), for Hawai'ian passerines (Moulton & Pimm, 1986), vertebrates (Ehrlich, 1989), and insects (Crawley, 1987). In North America, 54% of the invaders (61% of the pest species) invade elsewhere, while only 15% of the non-invaders do so (p = 0.0001). In Hawai'i the difference is even more striking: 76% of the invaders invade elsewhere (79% of the pest species) and only 28% of the non-invaders do so (p = 0.0001).

Latitude range. Species from a broad latitudinal range are possibly more phenotypically and/or genetically variable than those that are not. These variations may allow them to succeed under the many temperature and other climate changes found along latitudinal gradients. There may also be a greater risk of accidental introduction. Successful invaders in Australia that are from South Africa have a wider range of latitude in their home range than unsuccessful invaders (Scott & Panetta, 1993). A study of the Poaceae and Asteraceae native to Europe found that species invasive in North America had a latitude range about 10° more than species that do not invade (Rejmánek, 1996). Species that have a greater latitudinal range were found to be associated more with the invasive species than non-invasive species in North America, with an average of 19.6 for invaders and 13.1 for non-invaders (p = 0.0001). There was no difference in Hawai'i.

Taxonomic. Using taxonomic relationships alone to evaluate risk of invasiveness is not advisable. Within a family or genus there may be very aggressive weeds and rare non-competitive species. However, there do appear to be some trends. There are some families and genera that do appear to contribute a number of very aggressive species and others that contribute none or few, even when the family is as large and as commonly introduced. For instance, in North America both the rose (Rosaceae) and heath (Ericaceae) families are very popular ornamental and agricultural species. However, the rose family is the most common among the invasive woody plants in the country, with 13 genera and 40 species (including 12 pest species, 16% of the total). The heath family is as large as the rose family (Mabberly, 1987) and is commonly introduced, but there are only four woody species invading in North America, and none of them are pests. In Hawai'i the trends were a little less clear, because the Fabaceae contributed the largest number of invaders (31 species) and non-invaders (15). However, in Hawai'i, families such as the Melastomataceae and Myrtaceae had a high level of invasiveness and the Rutaceae, Rubiaceae, and Malpighiaceae, though commonly grown, did not. This indicates that there are traits within these taxonomic groups that either facilitate or hamper invasive ability. Because these traits may be inherited from a common ancestor, related species may also have the traits. However, once again, caution must be given, because these are different species and they may differ in the traits affecting invasive ability.

Another theory is that invading species that have close relatives in the native flora may be more likely to invade because they are probably morphologically and physiologically similar to species that have already been able to adapt to the conditions. I compared invaders and non-invaders and found that those introduced species with native congeners (a total of 38 species) are significantly more likely to establish in Hawai'i than those without (G = 9.33, p = 0.02). There was no difference at the family level. It is also reasonable, however, to expect that species with traits different from those of native species may be able to exploit resources differently or lack herbivores or pathogens adapted to that taxonomic group. That is consistent with findings on European Poaceae and Asteraceae introduced into California (Rejmánek, 1996).

How Can We Use These Generalizations?

For every biological, geographic, and taxonomic trait listed above as associated with invaders, one can easily list non-invasive species that also have the trait and vice versa. Then how do we use the patterns we have detected? Multivariate methods give us some ways of combining traits and, as mentioned, in the Methods section, two different techniques, discriminant analysis and classification and regression trees, were used. Only the results from North America are discussed here.

Table 1. Predictive model using discriminant analysis. Coefficients indicate the importance of the trait to the model (high values indicate importance).

Trait	Invaders	Non-invaders
Invades elsewhere	3.837	2.263
Native North America	10.919	14.453
Seed stratification	4.179	5.077
Hybrid	11.685	14.575
Vegetative reproduction	2.807	1.389
Minimum juvenile period	0.011	0.124
Semi-evergreen leaves	4.629	3.857
No seed pretreatment	5.193	4.401
Native temperate Asia	10.874	11.313
Native Great Britain/Europe	12.306	10.958
Native Mediterranean	11.087	11.639
Fruiting length	0.726	0.528
Flowering length	0.210	0.192
Evergreen leaves	3.552	5.060

The discriminant analysis used a combination of 14 traits to predict invasive ability. Some of the traits did not differ when invaders and non-invaders were compared, but were helpful in discriminating when combined with other traits. The traits used are listed in Table 1. Two tests to validate the model were made using two different sets of randomly selected species. A total of 88% of the species were correctly predicted the first time (96% of the invaders and 76% of the non-invaders, using 76 species) and 92% the second time (92% of both the invaders and non-invaders, using 63 species).

Classification and regression trees are usually "pruned" to produce the shortest tree possible and still retain accuracy. The tree chosen used only four traits (Figure 1). They were, in descending order, whether or not a species was a North American native, whether it vegetatively reproduced, whether it was a hybrid, and whether it invaded anywhere else. This tree was accurate in predicting 76% of the time based on only these four traits, with 73% of the invaders (114/157

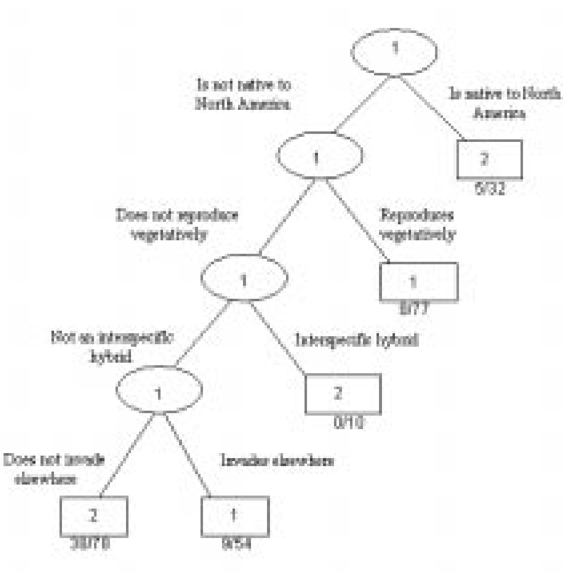

Figure 1. *Pruned classification and regression tree. Numbers under each node indicate the number of species identified by that trait, or combinations of traits (right of the slash), and the number of those incorrectly identified (to the left of the slash).*

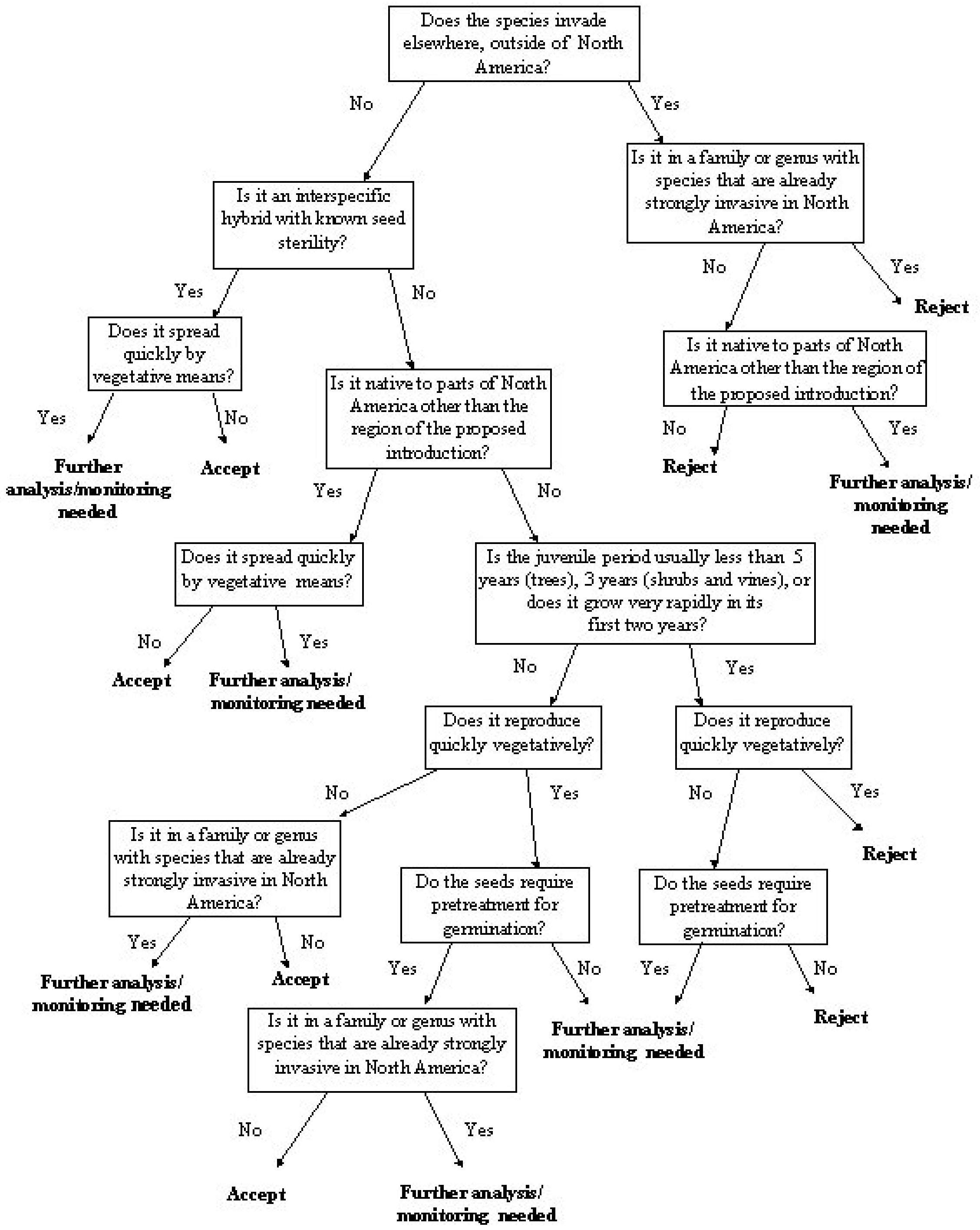

Figure 2. *Decision tree to evaluate invasive potential of woody plants in North America.*

species) and 82% of the non-invaders (77/94 species) correctly predicted overall.

The results of the comparisons, the discriminant analysis, and the classification and regression trees, were combined into a multi-path decision tree (Figure 2). The decision tree is purposely easy to use and low in technological requirements, in order to make it useable by everyone in the horticultural industry, its intended users. By responding "yes" or "no" to a series of questions, the user makes a determination of probable invasive ability. There are three outcomes: a species may be accepted because of a low probability of invasiveness, it may be rejected because it has a high probability of invasiveness, or it may be recommended for further evaluation, including quarantine and monitoring in field trials and further examination of its biology. There are numerous paths to each outcome and there is no single answer. Most of the species can be eliminated on the first branch of the tree if invasive elsewhere, but even if that information is unavailable, the tree is highly effective at evaluating invasive ability. The first half of the tree requires very little time or effort to determine. A trip to a well-equipped library is generally sufficient. Much of the information is now available over the World Wide Web, and on-line abstract services make finding papers written about the species very easy. Even species that seem obscure have often been researched for various uses. For those not near a large university library, papers can be secured through inter-library loans once the citation is found. The second half of the tree may require some estimation of growth rate and determination of seed germination requirements. Therefore, it is preferable to eliminate a species on the higher branches of the tree.

The decision tree correctly predicted 85% of the invasive species (174/204 species) and recommended that an additional 13% have further evaluation. Three invasive species were accepted, but these were not pest species. It was less successful at predicting a lack of invasive ability: only 46% of the species (40/87) were accepted outright, although another 36% (31/87) of the species were recommended for further evaluation and might ultimately end up being accepted.

Phase 3: Impact

Impact is an interaction of the traits of the invading species and the biotic and abiotic components of the invaded system. Thus, it is more difficult to detect invaders that may have an impact on an ecosystem in the earliest phases of an invasion because it requires a simultaneous assessment of the traits of the species and the traits of the ecosystems. Some generalities we can make, but the limited number of documented case studies makes extrapolation of these generalities difficult.

Examples of Impact. High competitive ability. Many invasive species are extremely competitive with natives and are able to capture more resources to the detriment of the natives. Examples of this include *Crataegus monogyna* Jacq., which has higher seed crops and larger and pulpier fruits than a related native congener. These larger fruits attract more birds and are consumed at a greater rate than those of the natives and affect patterns of distribution and abundance of the two species (Sallabanks, 1993). A more typical example would include species with aggressive roots that are known to extract water and/or nutrients from the soil at high rates, depleting these resources. However, it should be noted that many studies purporting competition are often poorly designed to demonstrate a true competitive interaction (Parker & Reichard, 1998). To develop predictive methods one would have to understand the ability of a species to extract a particular resource that might be limited in that particular community.

Introduction of structural changes. Some ecosystems are dominated by aggregates of particular life forms. For instance, grasslands generally consist of a mixture of grasses, forbs, and some woody shrubs. The introduction of an aggressively reproducing tree, in combination with management such as fire suppression, can result in conversion to forest. Another example might be floating mats of plants such as giant Salvinia (*Salvinia molesta* Mitch.) in open freshwater aquatic systems. This type of impact would require an understanding of a particular vulnerable ecosystem and the introduction of a species of a different life form that is capable of establishing there.

Nitrogen fixation. As already mentioned, some plants have bacteria-containing nodules on their roots that allow the plant to convert atmospheric nitrogen to a form useable by the plant. In addition to the plant using the nitrogen for growth, some is leaked out into the surrounding soil, increasing the nitrogen levels. In communities that commonly have low nitrogen content in the soil, such as prairies or soil of recent volcanic origin, the introduction of nitrogen can be a substantial change and can change community composition and succession (Vitousek et al., 1987; Stock et al., 1995). While nitrogen fixation is associated with the legume family, several plant families have species that are capable of fixing nitrogen. As already demonstrated above, nitrogen fixation is positively correlated with invasive ability. The impact of a nitrogen fixing species would be highest in communities that are known to have limited amounts of nitrogen available to plants.

High water depletion. *Tamarix ramossissima* Ledeb. has an unusual combination of traits that allow it to have a very high impact on communities in which water is limited. This species is a phreatophyte, with a tap root capable of extending down to even deep water tables (Horton et al., 1960). Plants have very high rates of transpiration, using from 0.7 to 3.4 m^3/year (Weeks et al., 1987). When this species grows in dense stands, the effect of transpiration rates can be increased substantially. This combination allows the plants to act almost as straws, removing high volumes of water and decreasing the water available to native species in the intermountain west, where it has freely established. This case, a combination of unusual plant traits combined with establishment in an ecosystem that is extremely limited in water most of the year, illustrates how difficult it is to anticipate impacts of species without consideration of the ecosystems it might invade. This species in an area with more ground water or more deeply rooted species would have far less impact.

Increase of fire frequency/intensity. There have been a number of cases where introduced invasive plants have altered the fire regime of the invaded ecosystem. There may be an increase in the intensity or frequency of fires due to an accumulation of flammable standing dead material. For example, cheatgrass (*Bromus tectorum* L.) is an annual grass that dies early in the spring and provides ample dry material during the fire season of the intermountain west. It has changed the fire return interval in Idaho from 60 to 110 years to 3 to 5 years (Whisenant, 1990). In Oregon, sites that are dominated by cheatgrass are considered 500 times more likely to burn than those with other cover (Stewart & Hull, 1949). Understanding and predicting this impact in early detection stages would require knowing something about the flammability and biomass accumulation of a species, the fire regime of the invaded ecosystem, and the tolerance of the existing species.

The examples given above are not intended to be an exhaustive list of the types of impacts that invasive plant species may have, but to illustrate the current difficulty in anticipating the impact of a newly detected invasive species. First the attributes of the species must be understood, then the types of ecosystems that it could potentially colonize must be determined, and lastly the attributes of the ecosystem combined with the species traits must be assessed. While we may someday have the ability to perform rapid assessment of impact after detection, we currently lack the ability to do this with any level of sophistication.

Conclusion

The need to analyze invasive ability before invasions occur or at the earliest stages is undeniable. Study after study shows the damage that invasive species do to native species, ecosystems, agriculture, and human welfare. By increasing our knowledge of the traits of species that may contribute to their introduction, establishment, and impact, we gain the ability to rapidly assess and control new species before they become so widespread that we are unable to instigate effective control methods.

Differences found between invaders and non-invaders were not uniform between North America, which is mostly temperate, and Hawai'i, which is tropical, except for some higher altitudes. This suggests that different traits may affect invasive ability between tropical and temperate areas, and that where risk assessment is concerned, perhaps "one size does not fit all." Defining where the limits lie and how inclusive we can be is one of our undiscovered challenges.

In searching for patterns that allow predictions, and in using them for assessing risk of establishment, there are a few things to consider: The traits used should be fairly easy and quick to determine. Traits such as self-compatibility or large number of seeds per plant may be related to invasive success, but the difficulty in determining them will discourage and delay evaluations. The traits should be clearly measurable. Traits such as "wide ecological niche" and "phenotypic plasticity" are too amorphous for practical use. Ask how you would measure the trait and how quickly you would be able to achieve a measurement. If the answer is not immediately apparent, this is not a good trait to use.

1. As few traits as possible should be used while still retaining accuracy. More traits do not necessarily increase efficacy, and they may well increase the likelihood that there will be more "unknowns" in the process, leading the species into a "further analysis" or "quarantine" position that will delay an ultimate decision (see Tucker & Richardson, 1995). An extensive laundry list of traits to determine may also discourage someone who is trying to make an assessment voluntarily.

2. The positive traits of a species should be considered separately from invasive potential. At issue is, first and foremost, whether a species is likely to become invasive. Then it should be decided whether positive attributes mitigate the invasive risk. Combining them clouds the issue.

3. Assume that any species introduced into a country will be distributed throughout the entire country. The species may not be entering in an area or climate where it is expected to survive, but it will probably not stay there. The chance of accidental spread is great, and for ornamental species, gardeners are generous and acquisitive to a fault. Thus, decisions on whether to accept a species or not should be made on the basis that it could become invasive in any part of the country. Regional assessments can be made to determine the areas most likely to be affected, and monitoring set up in those areas, but not to determine entry into a country.

4. The chosen methods should be flexible enough to incorporate new information. We are rapidly discovering more information about invasive plants, and methods should be updated to incorporate that information.

References

Baker, H.G. 1965. Characteristics and modes of origin of weeds. In: The Genetics of Colonizing Species, H.G. Baker and G.L. Stebbins (eds.). Academic Press, New York, pp. 147–172.

Baker, H.G. 1974. The evolution of weeds. Annual Review of Ecology and Systematics 5:1–24.

Blackburn, W., R.W. Knight and J.L. Schuster. 1982. Saltcedar influence of sedimentation in the Brazos River. Journal of Soil and Water Conservation 37:298–301.

Bock, J.H. and C.E. Bock. 1992. Vegetation responses to wildfire in native versus exotic Arizona grassland. Journal of Vegetation Science 3:439–446.

Brieman, L., J.H. Friedman, R.A. Olshen and C.J. Stone. 1984. Classification and Regression Trees. Wadworth International Group, Belmont, California, 358 pp.

Carmen, J.G. and J.D. Brotherson. 1982. Comparison of sites infested and not infested with saltcedar (*Tamarix pentandra*) and Russian olive (*Elaeagnus angustifolia*). Weed Science 30:360–364.

Crawley, M.J. 1987. What makes a community invasible? Symposium of the British Ecological Society 26:429–453.

D’Antonio, C.M. and P.M. Vitousek. 1992. Biological invasions by invasive grasses, the grass/fire cycle and global change. Annual Review of Ecology and Systematics 23:63–87.

Ehrlich, P.R. 1989. Attributes of invaders and the invasion process: vertebrates. In: Biological Invasions, a Global Perspective, J.A. Drake, H.A. Mooney, F. diCastri, R.H. Groves, F.J. Kruger, M. Rejmánek and M. Williamson (eds.). John Wiley and Sons, London, pp. 315–328.

Forcella, F., J.F. Wood and S.P. Dillon. 1986. Characteristics distinguishing invasive weeds within *Echium*. Weed Research 26:351–364.

Grubb, P.J. 1983. The ecology of establishment. Ecology and Design in the Landscape, A.D. Bradshaw, D.A. Goode and E.H.P. Thorp (eds.). Blackwell Scientific Publications, Oxford, pp. 83–95.

Hester, A.J. and R.J. Hobbs. 1992. Influence of fire and soil nutrients on native and non-native annuals at remnant vegetation edges in the Western Australian wheatbelt. Journal of Vegetation Science 3:101–108.

Horton, J.S., F.C. Mounts and J.M. Kraft. 1960. Seed germination and seedling establishment of phreatophytic species. Research Paper RM–48. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado.

Huenneke, L.F. and J.K. Thomson. 1994. Potential interference between a threatened endemic thistle and an invasive nonnative plant. Conservation Biology 9:415–425.

Mabberly, D.J. 1987. The Plant Book. Cambridge University Press, Cambridge, 706 pp.

Melgoza, G., R.S. Nowak and R.J. Tausch. 1990. Soil water exploitation after fire: competition between *Bromus tectorum* (cheatgrass) and two native species. Oecologia 83:7–13.

Mesléard, F., L.T. Ham, V. Boy, C. van Wijick and P. Grillas. 1993. Competition between an introduced and an indigenous species: the case of *Paspalum paspaloides* (Michx) Schribner and *Aeluropus littoralis* (Gouan) in the Camargue (southern France). Oecologia 94:204–209.

Meyer, P.W. 2000. Plant collecting expeditions: a modern perspective. Plant Exploration: Protocols for the Present, Concerns for the Future, J.R. Ault (ed.). Chicago Botanic Garden, Chicago, Illinois, pp. 7–13.

Moulton, M.P. and S.L. Pimm. 1986. Species introductions in Hawai’i. In: Ecology of Biological Invasions in North America and Hawai’i, H.A. Mooney and J.A. Drake (eds.). Springer-Verlag, Berlin, pp. 213–249.

Parker, I.M. and S.H. Reichard. 1998. Critical issues in invasion biology for conservation science. Conservation Biology for the Coming Decade, P.L. Fielder and P.M. Kareiva (eds.). Chapman and Hall, New York, pp. 284–305.

Pimentel, D., L. Lach, R. Zuniga and D. Morrison. 1999. Environmental and economic costs associated with non-indigenous species in the United States. <http://www.news.cornell.edu/releases/Jan99/species_costs.html> (June 12, 1999).

Rapaport, E. 1991. Tropical vs. temperate weeds: a glance into the present and future. In: Ecology of Biological Invasions in the Tropics, P.S. Ramakrishnan (ed.). International Scientific Publications, New Delhi, pp. 215–227.

Reichard, S.H. 1997. Prevention of invasive plant introductions on national and local levels. Assessment and Management of Plant Invasions, J.A. Luken and J.A. Thieret (eds.). Springer, New York, pp. 215–227.

Reichard, S.H. and C.W. Hamilton. 1997. Predicting invasions of woody plants introduced into North America. Conservation Biology 11:193–203.

Reichard, S.H. and P.S. White. *In press.* Horticulture as a pathway of invasive plant introductions in the United States. BioScience.

Rejmánek, M. 1996. A theory of seed plant invasiveness: the first sketch. Biological Conservation 78:171–181.

Rejmánek, M. and D.M. Richardson. 1996. What attributes make some plant species more invasive? Ecology 77:655–661.

Roy, J. 1990. In search of the characteristics of plant invaders. In: Biological Invasions in Europe and the Mediterranean Basin, A. diCastri, J. Hansen and M. Debussche (eds.). Kluwer Academic Press, Dordrecht, The Netherlands, pp. 335–352.

Saaty, T.L. and L.G. Vargas. 1991. Prediction, Projection, and Forecasting. Kluwer Academic Press, Boston.

Sallabanks, R. 1993. Fruiting plant attractiveness to avian seed dispersers: native vs. invasive Crataegus in western Oregon. Madrono 40:108–116.

Scott, J.K. and F.D. Panetta. 1993. Predicting the Australian weed status of southern African plants. Journal of Biogeography 20:87–93.

Stebbins, J.L. 1971. Adaptive radiation of reproductive characters of angiosperms II. Seeds and seedlings. Annual Review of Ecology and Systematics 2:237–260.

Stewart, G. and A.C. Hull. 1949. Cheatgrass (*Bromus tectorum*) – an ecological intruder in southern Idaho. Ecology 30:58–74.

Stock, W.D., K.T. Wienand and A.C. Baker. 1995. Impacts of invading N_2-fixing *Acacia* species on patterns of nutrient cycling in two Cape ecosystems: evidence from soil incubation studies and ^{15}N natural abundance values. Oecologia 101:375–382.

Thompson, J.D. 1991. The biology of an invasive plant: what makes *Spartina angelica* so successful? BioScience 41:393–401.

Tucker, K.C. and D.M. Richardson. 1995. An expert system for screening potentially invasive alien plant species in South African fynbos. Journal of Environmental Management 44:309-338.

U.S. Congress, Office of Technology Assessment. 1993. Harmful Non-Indigenous Species in the United States. OTA–F–565. U.S. Government Printing Office, Washington, DC.

United States Department of Agriculture. 1999. Agriculture Income and Finance situation and Outlook Report.

Vitousek, P.M., L.R. Walker, L.D. Whiteaker, D. Mueller-Dombois and P. Matson. 1987. Biological invasion by *Myrica faya* alters ecosystem development in Hawaii. Science 238:802–804.

Wagner, W.L., D.R. Herbst and S.H. Sohmer. 1990. Manual of Flowering Plants of Hawaii. The Bishop Museum, Honolulu.

Weeks, E.P., H.L. Weaver, G.S. Campbell and B.N. Turner. 1987. Water use by saltcedar and by replacement vegetation in the Pecos River floodplain between Acme and Artesia, New Mexico. Geological Survey Professional Paper 491–G. U.S. Geological Survey, Reston, Virginia.

Whisenant, S. 1990. Changing fire frequencies in Idaho’ s Snake River plains: ecological and management implications. Proceedings from the Symposium on Cheatgrass Invasion, Shrub Die-off and Other Aspects of Shrub Biology and Management. USFS General Technical Report INT–276, pp. 4–10.

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

Remote Sensing for Invasive Species and Plant Health Monitoring

Paul H. Greenfield
Remote Sensing Program Leader
USDA Forest Service
Salt Lake City, Utah

Abstract

The 21st Century promises great advances in the area of remote sensing for plant health monitoring. This paper describes the potential for various remote sensing tools and techniques to quantify the effects of invasive species, insect infestations, and diseases on plant health. The benefits of remote sensing include cost savings over ground surveys for large areas, the potential for simplified data entry into Geographic Information Systems, and a historical record of plant health for future analysis and change detection. Because of the vast number of topics and examples covered, this paper is very general in nature and intended to provide an overview of remote sensing for plant health monitoring and detection of invasive species.

Information is presented to provide a basic familiarization with current remote sensing practices and fundamentals for plant health monitoring. This includes a review of the electro-magnetic spectrum, sensor systems currently available for data acquisition, airborne and space-based imagery, the use of color infrared imagery, airborne video systems, and hyperspectral imaging techniques. Also presented will be general image processing tools that can be used to determine vegetative stress and detect change.

A number of remote sensing projects are presented that will acquaint the reader with the level of effort required to perform similar work at other locations. Included are specific projects to detect and map invasive species and vegetative stress. These include noxious weeds in the western United States, the use of color infrared imagery for insect and disease infestations on forested lands, the application of airborne video coupled with global positioning system information for Chinese tamarisk (*Tamarix chinensis*) infestations, and an aquatic weed project in Texas.

Remote Sensing Fundamentals

For plant identification, the visible and near infrared portions of the electromagnetic spectrum are often utilized to produce imagery. The reasons for this date back to the earliest use of color infrared film photography and the related methodologies and techniques that have been formulated over the years. Color infrared photography utilizes the green, red, and near-infrared portions of the spectrum. The amount of reflected energy for vegetation tends to be about five times as great in the near-infrared portion of the spectrum as opposed to the visible green portion of the spectrum. For this reason, remote sensing specialists are able to utilize this higher energy to record more detail and, potentially, subtle differences between adjacent vegetation.

Some common types of remote sensing tools discussed in past literature are satellite imagery, aerial photographs, aerial video, digital multispectral scanners, and digital cameras. Each offers unique information and has specialized niches that make it suitable for specific applications. For example, satellite imagery can provide digital images of very large areas but offers coarse spatial resolution. In contrast, traditional aerial photographs can provide high spatial resolution but may only cover small areas of land. Because of these kinds of trade-offs, knowledge of the problem at hand is critical to choosing the proper remote sensing tool.

Space-Based and Airborne Imagery

There are basically two different platforms utilized for acquiring remote sensing imagery: space-based and

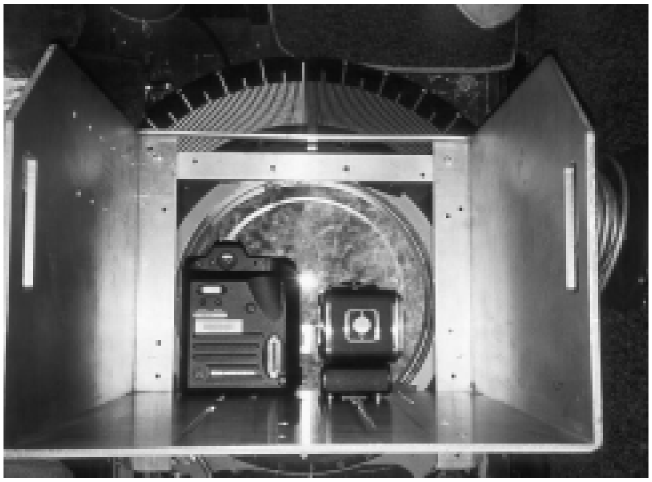

Figure 1. *A Kodak DCS 420 color infrared digital camera installed alongside a Hasselblad 70 mm film camera provides two types of imagery from a light aircraft.*

airborne. Space-based imagery potential is advancing rapidly, and we now have the first high resolution sensor available for vegetation management. The Ikonos system, launched by Space Imaging, Incorporated of Thornton, Colorado, can provide one meter black-and-white digital imagery as well as four bands (blue, green, red, and near infrared) of four meter imagery. A single scene size is 11 km by 11 km and the scene can be orthorectified to produce a 12.2 meter map accuracy product. Previously, the best resolution for multi-spectral imagery consisted of 20 meter SPOT imagery, or 30 meter Landsat Thematic Mapper imagery. Both of these two latter systems have provided many years of affordable, quality products, but suffered somewhat from their relatively coarse spatial resolution. It should be noted that both SPOT and Landsat TM offer potentially valuable historic information on extent of vegetation cover, and much good work has been done utilizing these two data sources.

Airborne systems have offered the remote sensing community the majority of imagery over the past 50 years. Because detection and monitoring of invasive species often requires acquiring imagery of very small targets such as noxious weed infestations, a low-altitude approach is often desirable. Airborne systems can carry relatively inexpensive sensors at low altitudes, which can result in high resolution imagery being available for later analysis. Sensor packages range from traditional resource photography equipment, such as the 9 inch by 9 inch film cameras, to compact digital cameras capable of on-the-ground pixel sizes of six inches or less, and advanced multi- and hyper-spectral imagers (Figure 1).

Active remote systems, such as radar and lidar, have the potential to detect invasive species if the plant shape or plant habitat lends itself to the limitations of these devices. These devices are present in both space-based and airborne configurations, but airborne systems perform the majority of functions for any potential invasive species detection and monitoring. This is due to the high spatial resolution that is generally required. As these systems continue to advance, it will be possible to determine the locations of smaller species if sufficient information is known about surrounding vegetation and plant characteristics.

Remote Sensing Benefits

Information gathered from remote sensing has been shown in various literature studies to be useful for mapping and monitoring invasive species infestations. The advantages of using remote sensing for mapping and monitoring invasive species are numerous, but most importantly it provides a unique perspective not attainable from the ground. Other advantages include large area coverage and collection of unique spectral information sometimes not visible with the human eye.

Noxious Weeds

Noxious weeds are considered an increasing problem throughout the United States. What distinguishes noxious weeds from other plants is that they are typically not native to the area in which they are invading, often growing unchecked by natural predators such as insects. A common characteristic of most noxious weeds is their aggressive, competitive behavior. They are typically a poor replacement for native vegetation in terms of their resource value to the ecosystem. Noxious weeds often become established in soil disturbed by construction, travel, recreation, etc., and are then transported by wildlife, livestock, machinery, vehicles, people, wind, and water to new sites. Once established, they have the capacity to invade adjacent, undisturbed natural plant communities. These characteristics allow noxious weeds to progress from small, manageable infestations to large, economically and environmentally damaging situations.

As awareness of the magnitude of the problem has grown, the USDA and other government departments are developing strategic plans for noxious weeds (refer to *The USDA Noxious Weed Strategy*, May 30, 1996). Critical needs identified in this document include early detection of new infestations and monitoring of existing infestations. Current ground-based surveys require a significant commitment of human and monetary resources to cover a relatively small percent of land area. The result can be slow response time and limited information on the extent and spread of noxious weeds. Remote sensing technologies offer the potential for early detection and can cover larger areas at lower costs than conventional ground surveys. The objective of this paper is to review what has been accomplished through the use of remote sensing for mapping and monitoring noxious weeds.

Noxious Weeds – Historical Perspective

Historically the native grasses of rangelands in the western United States were bunchgrasses, such as bluebunch wheatgrass (*Agrypyron spicatum*) and Idaho fescue (*Festuca idahoensis*). By the late 1800s, overgrazing and the inadvertent introduction of winter annual grasses such as downy brome (*Bromus tectorum*) and medusahead (*Taeniatherum caput-medusae*) had dramatically altered rangeland species composition. In turn, the winter annual characteristics and a vigorous taproot system of noxious weeds, such as yellow starthistle (*Centaurea solstitialis*), spotted knapweed (*Centaurea maculosa*), and dyer's woad (*Isatis tinctoria*), allowed them to outcompete the perennial and annual grasses. Because livestock tends to avoid the weeds, grazing on the grasses instead, the rangeland species composition shifted yet again to one dominated by the noxius weeds (Callihan & Evans, 1991).

Literature Studies - Mapping, Monitoring, and Detection of Noxious Weeds Using Remote Sensing

Many noxious weeds have biological characteristics that may make them detectable from remote sensing imagery. These characteristics include but are not limited to: 1) phenological differences from surrounding vegetation are often pronounced; 2) reflectance of weed leaves and/or flowers is often unique; 3) areas of weed infestations may be homogeneous and cover large areas; 4) habitat requirements are often predictable. Everitt et al. (1995) list several plant species that can be distinguished, and in some cases measured, by remote sensing. These species include silverleaf sunflower (*Helianthus argophyllus*), Texas lantana (*Lantana horrida)*, broom snakeweed (*Gutierrezia sarothrae*), false broomweed (*Ericameria austrotexana)*, spiny aster (*Aster spinosus*), blackbrush (*Acacia rigidula*), huisache (*Acacia farnesiana*), Mexican palo-verde (*Parkinsonia aculeata*), common goldenweed (*Isocoma coronopifolia*), drummond goldenweed (*Isocoma drummondii*), Chinese tamarisk (*Tamarix chinensis*), pricklypear (*Opuntia lindheimeri*), Big Bend locoweed (*Astragalus mollissimus* var. *earlei*) and shin oak (*Quercus havardii*).

The studies referenced below are ordered by topic of biological characteristic. Journals reviewed for this paper include *Photogrammetric Engineering & Remote Sensing*, *Remote Sensing of Environment*, *International Journal of Remote Sensing*, *Journal of Range Management*, *Weed Science*, and *Weed Technology*. Additional information has come from scientific conference proceedings.

Phenological Differences of Noxious Weeds

A common characteristic found in the literature that allows many noxious weeds to be detected using remote sensing is that many species have unique phenological characteristics when compared with surrounding vegetation. Noxious weeds are often actively growing early in the growing season, before green-up of native vegetation, or remain green later into the growing season, after native vegetation has senesced. The often unique phenological characteristics associated with noxious weeds can assist in their detection by remote sensing even if the targeted noxious weed appears similar to the surrounding vegetation during other times of the year.

In numerous studies, successful mapping of the target weed was attributed to unique phenological characteristics. An early study reported by Armstrong (1979) identifies late June to early July during full bloom as the best time to image leafy spurge (*Euphorbia esula*) using color infrared photography. The appearance of leafy spurge on color infrared imagery at this time is described as "hot pink," and it is not easily confused with other vegetation. The author also recommends imaging at a scale of 1:24,000 or larger to adequately image small leafy spurge patches, and reports successfully imaging 100 ft^2 patches at 1:24,000. A later study by Everitt et al. (1995) used color and color infrared photography as well as color video imagery to detect and map leafy spurge infestations. Acquired at peak flower, the leafy spurge bracts were a distinct yellow-green on the conventional color photography and were pink on the color infrared photography. Leafy spurge infestations could be delineated on both types of photography, the scales of which ranged from 1:10,000 to 1:15,000. However, sparse stands or clumps with less than 25% canopy cover and single plants were generally not distinguishable. The authors felt that neither film type was superior to the other. On the conventional color video imagery, leafy spurge exhibited a golden-yellow image response. The resolution of the video imagery acquired for this project was coarser than that of the photography, thus limiting the ability of the video imagery to detect small stands or clumps of leafy spurge. The Forest Service has had

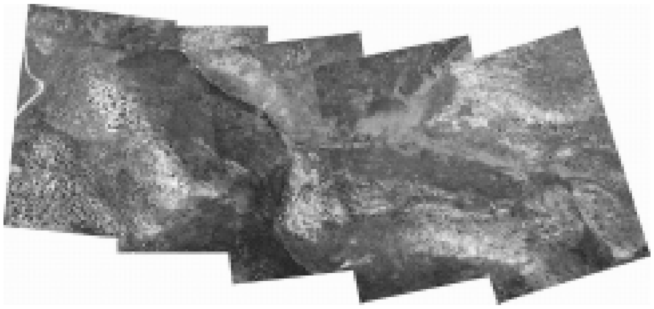

***Figure 2.** A digital camera mosaic of leafy spurge infestation on the Caribou National Forest in Idaho.*

success detecting leafy spurge on color infrared digital camera imagery (Figure 2). Fall color is another phenological period in which leafy spurge typically stands out from surrounding vegetation (Francis et al., 1980)

In another study (Richardson et al., 1985), six various cover types including five agricultural crops and pigweed (*Amaranthus palmeri*) were studied using low altitude (900 m) color infrared aerial video. The study showed that this particular weed appears more vigorous than the agricultural crops early in the growing season and can best be discriminated from agricultural crops using near infrared [0.85–0.89 micrometer (µm)] wavelengths. Discrimination proved even better when using a multidate comparison of video images from two dates during the growing season (May and July). The multidate imagery increased the accuracy of classification from 75% (May) to 88% (May and July combined). In a similar study by Menges et al. (1985), the reflectance of several additional weeds such as climbing milkweed (*Sarcostemma cyanchoides*), ragweed parthenium (*Parthenium hysterophorus*), and johnsongrass (*Sorghum halepense*) mixed with agricultural crops were studied. Color infrared transparencies at a scale of 1:8,000 were used to map the weeds. According to the research, successful mapping of the weeds was aided by differential stages of inflorescence and senescence as well as other characteristics.

In a later study, Everitt and Deloach (1990) determined that the optimum phenological stage for distinguishing Chinese tamarisk (*Tamarix chinensis*), an exotic shrub, on color aerial photographs was in the late summer–early fall period when its foliage turned a yellow-orange. In follow up studies, Everitt et al. (1992) reported that false broomweed (*Ericameria austrotexana*) and spiny aster (*Aster spinosus*) could be detected on color infrared aerial photographs during their mature vegetative stages in spring and summer. Even with a lower resolution color–infrared video system, they were able to distinguish small stands of each of these weeds and provide area estimates (Figure 3). However, due to lower spatial resolution, video was not useful for detecting individual plants.

***Figure 3.** Aerial video imagery of Chinese tamarisk (*Tamarix chinensis) *along the Rio Grande River in Texas.*

Common (*Isocoma coronopifolia*) and drummond goldenweed (*Isocoma drummondii*) are weeds that often invade rangelands in southern Texas. Reflectance measurements made on both species showed that they had higher visible reflectance than did associated plant species during flowering (Everitt et al., 1992). Both common and drummond goldenweed could be detected from other plant species on large scale color aerial photographs (1:1,500 to 1:2,900 scale). The authors found that color photographs were superior to color infrared photographs for distinguishing both species, and that they could only be identified using remote sensing at flowering. In another study, Everitt et al. (1993) found that even color aerial videography could be used to discriminate blackbrush acacia (*Acacia rigidula*) and huisache (*Acacia farnesiana*). These are two weeds that invade Texas rangelands and cause brush problems. This study and others have confirmed that identification of blackbrush acacia and huisache on aerial imagery is due to their unique spectral reflectance during flowering. The authors found that the visible areas of blue and green were of particular importance in distinguishing flowering huisache while the green and the red areas were best for distinguishing blackbrush acacia from the other shrubs and vegetation.

False broomweed (*Ericameria austrotexana*) infestations in Texas were found to be mappable even from SPOT multispectral satellite imagery when the foliage of the shrub was fully developed and during periods of low herbaceous biomass production (Anderson et al., 1993). The authors found that during drought conditions the only green biomass present was from tree and shrub species, including false broomweed. The limited herbaceous vegetation growth resulted in low values in the near-infrared and red portions of the

spectrum relative to the other classes.
In another study (Peters et al., 1992), low-spatial resolution satellite imagery was found to be useful for discriminating broom snakeweed (*Gutierrezia sarothrae*) in the grasslands of central New Mexico. In this study, Advanced Very High Resolution Radiometer (AVHRR) satellite imagery with a spatial resolution of 1.1 km was used in a multi-date study. The authors found that the best discrimination occurred in early spring, as broom snakeweed has an early season growth flush while most of the native warm season grasses green-up later in the season.

Unique Reflectance Characteristics and the Homogeneous Nature of Invasive Species

In addition to phenological differences, some invasive species have unique spectral characteristics that may help to distinguish them from surrounding land cover. Leaf structure and function result in variations in the absorption and reflection of solar radiation from plant canopies (Tucker & Sellers, 1986). Chlorophyll content, flowering characteristics, vegetation, background soils, life-form, etc., all have an effect on how the plant may appear on remote sensing imagery. Studies have shown that there are two spectral regions where remote sensing is particularly useful for discriminating vegetation. The upper portion of the visible (0.6–0.7 m) and the near infrared (0.75–1.1 m) have been shown to infer properties related to pigment absorption, green leaf density, and canopy leaf water content. These regions provide a strong signal from the vegetation and provide spectral separation from most background materials such as soils (Tucker & Sellers, 1986).

In a study using a four camera video system with sensor capability ranging from visible to near-infrared light (0.41–10 m), Everitt and Nixon (1985) were able to discriminate woolly stemodia (*Stemodia tomentosa*) from other vegetation in the blue (0.42–0.45 m) wavelengths, while minimal differences were noted in the near infrared wavelengths. This difference in the visible wavelengths was attributed to the plants' dense white hairs that cover the leaves and stem.

In a recent study, Everitt et al. (1994) determined that Big Ben loco (*Astragalus mollissimus*) and Wooton loco (*Astragalus wootonii*) could be quantified from other landscape features using color infrared video imagery and color infrared photographic prints at scales between 1:1,000 and 1:7,000. Reflectance measurements were made on each species with a hand-held radiometer. Throughout the growing season both plants showed higher near-infrared reflectance than any surrounding vegetation. This was the key factor in their identification on remote sensing imagery. Optimum scales for detecting individual plants and small populations were 1:1,000 to 1:3,000. However, the authors suggest that large format 23 cm film would be optimum for mapping locoweed populations over extensive areas because of wide ground cover and superior resolution. For example, a single roll of 23 cm film would photograph 14,900 ha at a scale of 1:5,000.

Finally, in a further study (Everitt et al., 1999), it was determined that spectral reflectance differences between two species of aquatic macrophytes resulted in good detectability for waterway invasive species. A three camera multi-spectral digital video system (Figure 4) was employed to acquire imagery of waterhyacinth (*Eichhornia crassipes*) and hydrilla (*Hydrilla verticillata*) in southern Texas waterways. Because waterhyacinth had a higher near infrared reflectance than surrounding vegetation, and hydrilla had a lower near infrared reflectance, the resultant imagery produced very accurate maps of aquatic weed infestation (Figures 5 & 6).

Figure 4. *Airborne three-camera video system employed for detection of aquatic macrophytes in Texas.*

Figure 5. *Video imagery of waterhyacinth (*Eichhornia crassipes*) and hydrilla (*Hydrilla verticillata*) along the Rio Grande River in Texas.*

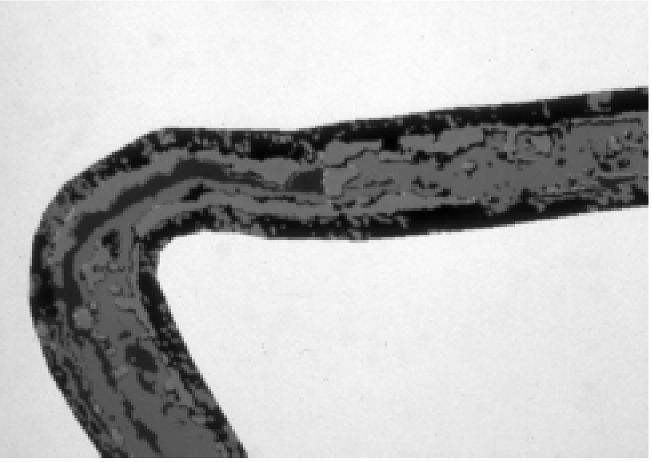

Figure 6. *Image processing enhancement of Figure 5 results in an accurate map of the two aquatic macrophytes.*

Predictable Habitat Requirements

In order for remote sensing to be cost-effective for detecting and monitoring invasive species, it is usually necessary to narrow the scope of the project area. In many instances, invasive species are highly correlated with certain cover types or conditions. Methods using remote sensing and geographic information systems (GIS) can be used to narrow the scope of data collection to only those habitats that are most likely to contain the invasive species. Martinko (1982) used Landsat Multispectral Scanner (MSS) satellite imagery to stratify a county into major cover-type categories determined on the basis of musk thistle (*Carduus nutans* L) habitat preference (i.e., pastures, wooded land or brush areas, old fields, and cropland). Large scale color infrared aerial photographs (1:3,800) were then acquired over these targeted areas during peak musk thistle flower. This use of remote sensing shows how images from various levels can be used in conjunction to map and monitor noxious weeds.

Dyers woad (*Isatis tinctoria*) infests crops and waste areas and is spreading at an alarming rate on western range and forest lands. In a recent study (Dewey et al., 1991), Landsat Thematic Mapper (TM) satellite imagery was used to identify specific land cover types associated with dyers woad. Out of sixty cover types mapped from the TM imagery in northern Utah, ten were found to be strongly associated with current dyers woad infestations based on field studies of 1,731 infestation points. The author’s opinion is that the use of satellite imagery and GIS predictive methods provides land resource managers with a powerful tool for estimating potential weed distribution over large, vegetatively diverse land areas.

The use of GIS is becoming an important tool for recording the location, size, and type of outbreak as well as for predicting plant habitat. In one study (Prather & Callihan, 1993), a GIS was developed specifically for eradication of the common crupina (*Crupina vulgaris*). This study illustrated how a GIS was used to develop a simple model for eradicating this weed through maintenance of a database for record keeping, sensitive area delineation, weed surveying, and developing control tactics.

Conclusion

Studies have shown that discrimination of numerous invasive species is possible using remote sensing. Because each species has unique growth characteristics, it is not possible to provide recommendations that would apply to all potential detection efforts. However, there are some common points brought up in past projects that illustrate the usefulness of remote sensing. It appears that there is no single best time of year to discriminate invasive species from surrounding land cover. Phenological differences between the plant and the associated vegetation should be studied carefully in order to identify periods of maximal differential reflectance for optimal remote sensing data collection. Some vegetation characteristics of the plant species may also lend themselves to detection by remote sensing. Flowering characteristics and leaf structure appear to be important to identifying weeds from remote sensing. Large area coverage imagery, such as satellite imagery, can be useful for delineating potential habitat of noxious weeds, and, in some cases, can even identify large infestations. However, higher resolution imagery, such as large scale aerial photographs or video, must be used in order to locate smaller infestations. With GIS, the advantages of using remote sensing are even greater. Information derived from remote sensing imagery can be used with other theme layers, such as slope, elevation, aspect, etc., to assist in locating infestations as well as to develop strategies for control.

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References

Anderson, G.L., J.H. Everitt, A.J. Richardson and D.E. Escobar. 1993. Using satellite data to map false broomweed (*Ericameria austrotexana*) infestations on South Texas rangelands. Weed Technology 7:865-871.

Armstrong, D.W., III. 1979. Aerial infrared imagery of leafy spurge (*Euphorbia esula*). In: Leafy Spurge Symposium, 26–27 June 1979, Bismarck, North Dakota, pp. 68–69.

Callihan, R.H. and J.O. Evans. 1991. Weed dynamics on rangeland. Noxious Range Weeds, pp. 55–61.

Dewey, S.A., K.P. Price and D. Ramsey. 1991. Satellite remote sensing to predict potential distribution of dyers woad (*Isatis tinctoria*). Weed Technology 5:479–484.

Everitt, J.H., M.A. Alaniz, D.E. Escobar and M.R. Davis. 1992. Using remote sensing to distinguish common (*Isocoma coronopifolia*) and drummond goldenweed (*Isocoma drummondii*). Weed Science 40:621–628.

Everitt, J.H., G.L. Anderson, D.E. Escobar, M.R. Davis, N.R. Spencer and R.J. Andrascik. 1995. Use of remote sensing for detecting and mapping leafy spurge. Weed Technology 9:599–609.

Everitt, J.H. and C.J. Deloach. 1990. Remote sensing of Chinese tamarisk (*Tamarix chinensis*) and associated vegetation. Weed Science 38:273–278.

Everitt, J.H., D.E. Escobar, M.A. Alaniz, R. Villarreal and M.R. Davis. 1992. Distinguishing brush and weeds on rangelands using remote sensing. Weed Technology 6:913–921.

Everitt, J.H., D.E. Escobar and M.R. Davis. 1995. Using remote sensing for detecting and mapping noxious plants. Weed Abstracts 44(12):639–649.

Everitt, J.H., D.E. Escobar, R. Villarreal, M.A. Alaniz and M.R. Davis. 1993. Integration of airborne video, global positioning system and geographic information system technologies for detecting and mapping two woody legumes on rangelands. Weed Technology 7:981–987.

Everitt, J.H. and P.R. Nixon. 1985. Video imagery: a new remote sensing tool for range management. Journal of Range Management 38(5):421–424.

Everitt, J.H., J.V. Richerson, M.A. Alaniz, D.E. Escobar, R. Villarreal and M.R. Davis. 1994. Light reflectance characteristics and remote sensing of Big Ben loco (*Astragalus mollissimus* var. *earlei*) and Wooton loco (*Astragalus wootonii*). Weed Science 42:115–122.

Everitt, J.H., C. Yang, D.E. Escobar, C.F. Webster, R.I. Lonard and M.R. Davis. 1999. Using remote sensing and spatial information technologies to detect and map two aquatic macrophytes. Journal of Aquatic Plant Management 37:71–80.

Francis, R.E., M.J. Morris, R.J. Myhre and D.L. Noble. 1980. Inventory and analysis of leafy spurge (*Euphorbia esula*) sites: a feasibility study. In: Northern Regional Leafy Spurge Conference, 17–18 December 1979, Billings, Montana.

Martinko, E.A. 1982. Remote sensing and integrated pest management: the case of musk thistle. Remote Sensing for Resource Management, pp. 172–178.

Menges, R.M., P.R. Nixon and A.J. Richardson. 1985. Light reflectance and remote sensing of weeds in agronomic and horticultural crops. Weed Science 33:569–581.

Peters, A.J., B.C. Reed, M.D. Eve and K.C. McDaniel. 1992. Remote sensing of broom snakeweed (*Gutierrezia sarothrae*) with NOAA–10 spectral image processing. Weed Technology 6:1015–1020.

Prather, S.T. and R.H. Callihan. 1993. Weed eradication using geographic information systems. Weed Technology 7:265–269.

Richardson, A.J., R.M. Menges and P.R. Nixon. 1985. Distinguishing weed from crop plants using video remote sensing. Photogrammetric Engineering and Remote Sensing 51(11):1785–1790.

Tucker, C.J. and P.J. Sellers. 1986. Satellite remote sensing of primary production. International Journal of Remote Sensing 7(11):1395–1416.

Surveys and Diagnostics 2000: Virtual Cart, Digital Horse, and Uphill Reality

Eric LaGasa
Chief Entomologist
Pest Program/Laboratory Services Division
Washington State Department of Agriculture

Abstract

Rapidly expanding global trade and personal travel are part of an economically driven amalgamating process that has the propensity, if not certainty, to mix together and homogenize the earth's biotic elements. This "mixing" inexorably includes global pest and disease organisms, the detection and monitoring of which have been conducted at the state level (in the "other" Washington) for the last 15 years. My presentation today is intended to provide an update on some new tools for collecting and managing digital information essential to the diagnostic processes we rely on for pest surveys. The "virtual cart" (in my presentation title) refers to the dynamic and often vaguely defined collective process we participate in as part of the existing system to deal with introduced exotic pests. The "uphill reality" is a function of the rapid growth of global trade and travel, which may make our task analogous to fishing in a waterfall. "Digital horse" refers to several new digital cameras and graphics applications that can provide us all the practical means to capture and exchange picture-based technical information essential to effective surveys. Digital cameras are now a functional and affordable tool for the instant capture of graphical information. The Nikon Coolpix® 950 and 990 cameras capture very high quality pictures, are easy to use, adaptable to varied conditions, and cost less than $1,000. Most importantly, they both have a built-in macro lens capable of sharp auto-focus to less than 1 inch. Digital cameras provide instant verification of photograph content and quality, which makes film photography archaic and expensive for many applications. Scanner technology is also now a practical and inexpensive means of converting existing (hard-copy) graphics to digital format for exchange and manipulation. Powerful new software applications make digital graphic manipulation and organization easy and fast. However, while the capture and exchange of digital graphics may become a workhorse of the regulatory survey and diagnostic processes, they will not replace the systematists and physical diagnostic resources necessary for definitive pest and disease identification.

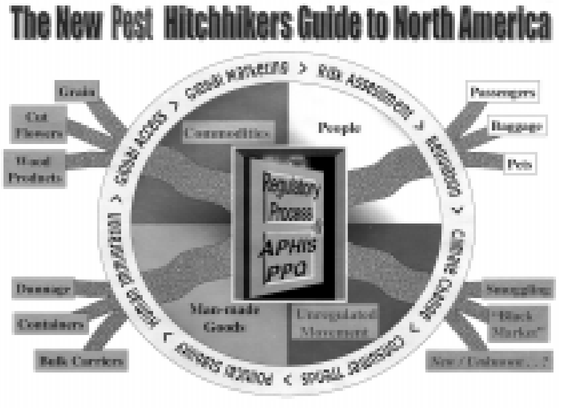
Introduction

The results of insect pest surveys seem to be more unpredictable than ever in recent years, as exotic species keep popping up with unsettling regularity.

Calls from homeowners, nursery operators, and landscape and forest managers reporting remarkable pests or damage they've "never seen before" are more ominous now than in 1983, when the picture was taken.

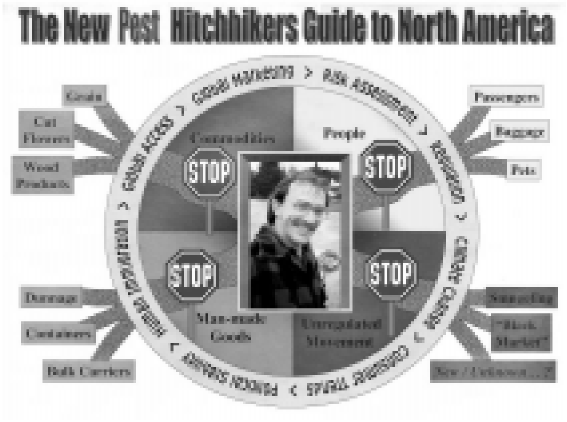
Fortunately, this Seattle backyard collection ended up being a fairly common "plastic" species, although somewhat confusing systematically. Unusual pests found in the following few years, however, began to produce a lengthy list of exotic species new to our corner of the country.

Expanding trade, opening new markets and bringing new commodities into the flow of commerce, is only one segment of the rapid growth in global movement.



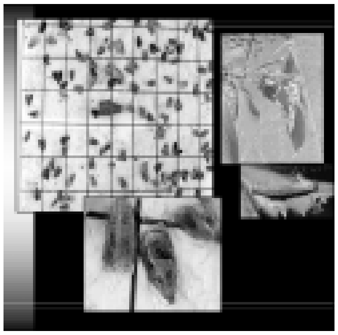
The graphic was prepared for a poster session at the 1997 NAPPO conference in Seattle, thus "North America" in the title. "APHIS, PPQ" has been inserted here where there was "NAPPO." It works well for consideration here, in that the pathways are many, and likely increasing.

Who stands behind the door, pressing to keep the pathways regulated and the door shut to damaging exotic pests and diseases?



It's our own Charles Schwalbe, Associate Deputy Administrator, USDA, APHIS, PPQ, shown here during his hands-on gypsy moth-bashing days in about 1985. Although he will undoubtedly deny having ever been in Bellingham, Washington, here he is, having more fun than a Methods Laboratory Director (his position at the time) should, and even in the rain. We, at the Washington State Department of Agriculture, owe Chuck, and his esteemed successor at the OTIS Laboratory, Vic Mastro, a huge thank you. They provided the critical "right stuff" to keep gypsy moth out of the Pacific Northwest during critical high-immigration years. More power to them and their APHIS cohorts now, as we face an expanding cast of invasive pests from distant corners.

CAPS Surveys



In the course of conducting a variety of CAPS exotic pest detection surveys over the last 10+ years, determining the presence or absence of the target species has generally been fairly straightforward. Target pest recommendations came with sufficient diagnostic information (as part of the pheromone, trap, and biology information package) to allow surveyors to identify, or at least screen, trap catch for potential target species.

However, one invariably frustrating facet of many surveys is the question "What are those <u>non-target</u> collections?" To try to identify all species collected in a survey is an appealing concept, particularly when using exotic pheromone lures or working in high-risk areas like ports. Screening non-target captures for potential new exotic introductions requires knowledge of the "background" or endemic species present, a knowledge base that does not exist or is very limited in many states. This is unfortunately the case for many insect groups in the Pacific Northwest.

Nevertheless, the discovery of several exotic fruit tree pests in Washington between the mid-1980s and early 1990s prompted us to begin to try to identify all species collected, targets and non-targets alike, at least from surveys for exotic pests of tree fruit.

Also, beginning in 1994, we initiated a series of CAPS surveys examining apple defoliators present in Western Washington, in which defoliator larvae were collected and reared to adult for identification.

For those who are not familiar with the "other Washington," most of the urban population of the state and industrial base is located in Western Washington, the Puget Sound area in particular. The Cascade Mountains form a major geographical barrier between the commercial apple-producing areas in Eastern Washington and the populous "west side."

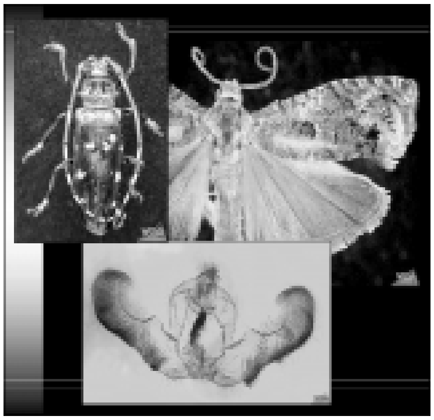
This bit of information is provided to show that the new pest occurrence information represents pests that do not occur in the major areas of commercial production at this point, a rather significant detail when negotiating export market access for a billion dollar commodity.

The summary table shows that the CAPS survey of apple defoliators was rather "fruitful" for new state and U.S. exotic species records between 1994 and 1995.

It is important to note here that all of the exotic species first-detection records from 1994 and 1995, with the exception of apple tortrix, were known (from the technical literature) to be established in British Columbia, Canada, and were anticipated to be present in Washington State. These new exotic species appear to have spread through natural dispersal into northwestern Washington, which is also the case for most of the other subsequent record captures shown here. However, apple tortrix, the new bark beetles, and the poplar shoot borer were all identified as non-target catches in surveys for other target species.

The process of rearing and identifying these new exotic species and the non-target native and known established exotic species has produced a substantial basis for a reference collection of regional Tortricidae, a resource that did not exist before. Building that collection and exploring new tools for developing and sharing diagnostic information, with limited resources, has become a CAPS project focus in Washington State. This is a good opportunity to share some of the exciting new technology that is now available and accessible, even to those on limited resources.

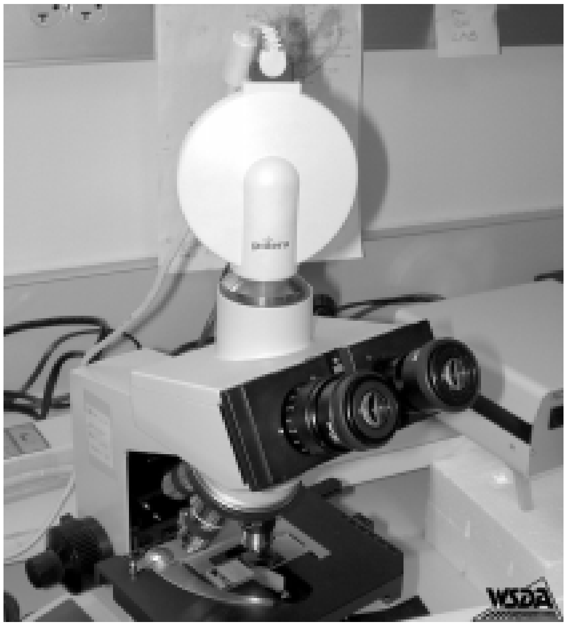
New Photographic Technology



We all know how many words a good picture is worth. This particularly is true for the process of identifying pest and disease organisms and the symptoms or damage they inflict. In the last two years, the ability to capture, manipulate, organize and share digital graphics has radically improved. But what may be the biggest surprise, as far as news, is the tremendous improvement in image quality and dramatic decreases in costs of hardware.

The widespread incorporation of digital imagery tools into our collective process will make critical information sharing much easier. Our "virtual cart" of participants and procedures involved in detecting and identifying introduced exotic pests should travel a bit faster with the horsepower that digital imagery provides. The tools are here now and will only get better (and cheaper).

As a real world example, two years ago the identity of the (now) familiar-looking beetle specimen pictured here was determined in less than 4 hours from the time it was brought into the Olympia office. This photograph was taken with a hand-held digital camera, without any special lenses, and the specimen was placed on a windowsill for lighting.

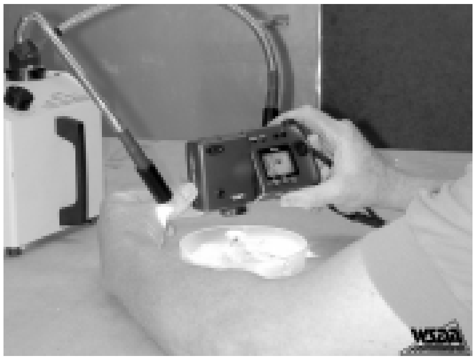


The camera shown here, sitting on top of a compound microscope, is a digital camera purchased in 1996. At the time, it was a fairly sophisticated camera, although it has no on-board memory and needed to be connected directly to a computer for image capture and storage. Manufactured by the PixEra company, it uses a process of combining several exposures to create a single 1200 x 900 pixel image. Besides the limiting lack of memory, the camera came with a small aperture lens, which provides a very shallow depth of field. However, for applications such as this where depth of field is not an important consideration, it works very well. When purchased, the camera and computer card required to connect the camera to a computer cost about $1,000. Comparable cameras today, <u>with</u> onboard memory and capturing the same size image, are available for less than $500. In any case, a relatively unsophisticated camera such as this can be a very useful tool in a number of situations.

When the Nikon CoolPix 950 camera (the lower camera pictured) came on the market about 3 years ago, the initial technical reviews of the camera and the image quality it produced were glowing. At the time, the CoolPix 950 with an 8 MB memory card cost about $1,000. While the image quality sounded great, the camera feature that clinched a purchase for me was the built-in macro lens with autofocus down to 0.8 inch.

Having purchased a CoolPix 950 and tried it out, I felt like I had a piece of hardware from the future. This little camera captures incredibly sharp images in up to 1,600 x 1,200 pixel format, and has every operational feature found in good quality film cameras. The autofocus macro capability is truly amazing. That feature, and the instant picture review capability, in many ways are a quantum leap over the bags of camera hardware and macro lenses many of us have dragged around for the last 30+ years.

Within a year, Nikon released the CoolPix 990, with even more sophisticated features including a 2,000 x 1,500 pixel format with a price tag around $1,000. Both models use the little compact flash-memory cards, shown here with the CoolPix 990 that can be purchased with as much memory as the budget will allow.



The pivoting parts and full color, high-resolution displays make these cameras very handy for macro photography as well as getting odd angles for regular pictures. The autofocus can take a few seconds to decide what’s right, which can make holding the camera steady at arm’s length a bit tricky. To compensate for this, both the Coolpix 950 and 990 have a “best shot selection” feature, in which they shoot a series of pictures in rapid succession then select the sharpest image in the set to send to memory.

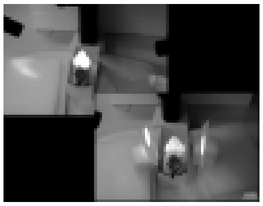
Taking pictures outdoors in bright sunlight makes the display difficult to see; however, both cameras have nice optical viewfinders. The optical viewfinders have handy bracket lines for centering the light metering and/or locking down the autofocus, which happens when the shutter is depressed half way. With a little practice, using the optical viewfinder also allows the display to be turned off, which saves considerable battery life.

With macro focus capability down to 0.8 inch from the lens, these cameras take great full-field pictures of objects the size of a nickel. With their large format capture capability, one can crop out even smaller subjects with fine detail.

The set of photographs where the actual picture taken is matched with the set-up in the upper picture gives a feel for the capabilities of these cameras. However, there is another trick for improving the illumination of the subject that makes a great difference in the quality of photographs taken with fiber-optic lighting.

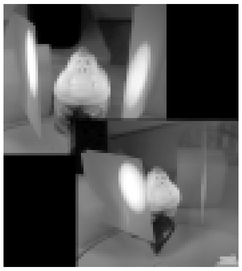
Fiber-Optic Lighting

Fiber-optic light diffusion is a lighting procedure that Henri Goulet introduced me to at one of the fabulous Hymenoptera workshops that he, Lubo Masner, and other excellent systematists conducted.

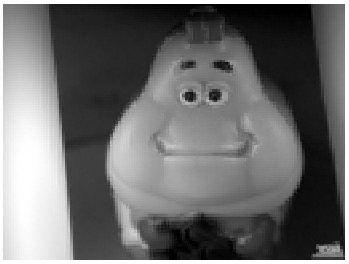


Essentially, light diffusing filters, when placed a few inches from the fiber-optic light sources and close to the subject, deflect and scramble the more or less coherent light beam. The result is that the light appears to be coming from many different angles and does a much better job of illuminating uneven surfaces.

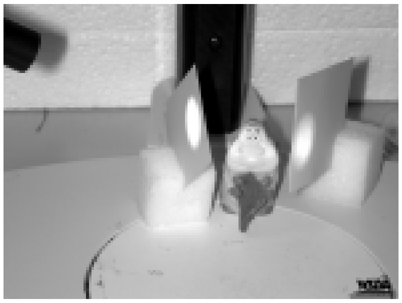
The “spare no expense” materials here are simple blocks of Styrofoam, into which are inserted cut pieces of the opaque white plastic material used as report covers. This is the kind of material that becomes fairly transparent when laid on text, but becomes an opaque white when lifted off text. The original material that Henri demonstrated at the workshop is a thicker white mylar material that is actually used to make diffusing filters for commercial photography and stage lighting. That material can be very difficult to find and this thinner material works almost as well.



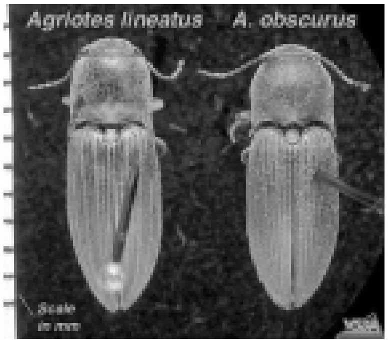
The photo shows how the filters do a nice job of dispersing the light when placed close to the subject. Generally, the closer the filters are placed to the subject, without having them interfere with the picture, the better.



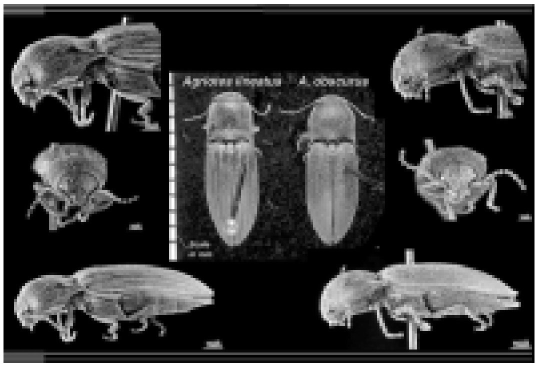
The closer view shows how light is dispersed evenly by the filter material. This effect is more pronounced the more irregular the surface, and can be quite dramatic in bringing out the textures on rough elytra and other insect structures. Again, under higher magnification, the smaller the texture detail, the better this works.



The pictures show a comparison with and without the diffusion filters. Although the fiber-optic light source on the left is about the same distance from the subject in both pictures, note that the subject is much more evenly illuminated overall by the filtered light.

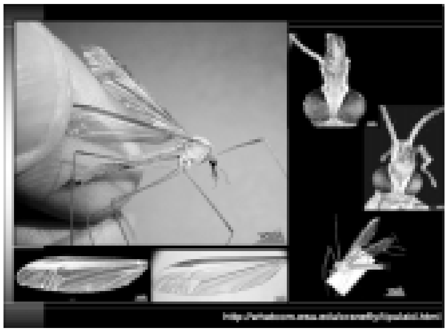


Next, let us look at some real examples of insect macro photography using the light-diffusing material. The scale marks on the left in the picture are millimeters.



These are the two European wire worm species that we collected in Washington State this year. A collage like this is easy to put together and works well for comparing the subtle morphological differences between these two species.

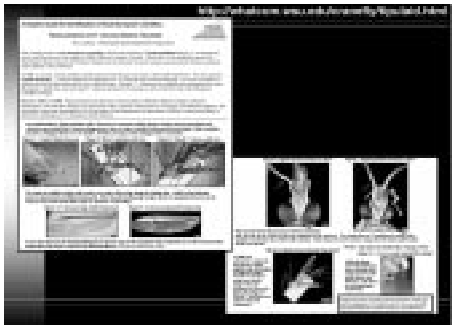
These pictures worked well as references for my field staff checking traps and my laboratory help re-checking specimens prior to data entry. For an additional feel for the scale of these pictures, note the relative size of the number 2 pins in these specimens.



In this picture are some examples of both hand-held photography and photomicrography of another new exotic resident from our corner of the country. These photographs were used to prepare a web page of diagnostic information to separate the new species from a close relative that has been in the Northwest for several decades.

A key morphological difference between the two species is illustrated in the two photographs of the under sides of the heads in the upper right. In the newcomer species, *Tipula oleracea*, the upper picture here, the space between the eyes ventrally is about the width of the diameter of the basal segments of the antenna. In comparison, the ventral eye separation is much wider on *Tipula paludosa*, usually several times the width of the antenna segments.

The lower photograph, with the arrows overlaid on the wing and abdomen, illustrate a character that can be used to separate females of these two species. *Tipula oleracea* females have wings noticeably longer than the abdomen.



This is the first page of the web site assembled to disseminate information on this new species. Creating these web graphic images was quick and easy with the little Nikon CoolPix 950.

Digital Imaging Hardwares

For the purposes of this talk, I visited my APHIS friends and compatriots at the Port of Seattle to check out the new digital imaging hardware they recently acquired and to see how it was working into their “cartload” of identification needs.

The veteran port plant pathologist, Dick Withee, had a pretty good handle on most of the new, high-powered tools.

The heart of the sophisticated set-up is a multiple CCD video camera that can be moved between the new dissecting microscope, a high-powered compound microscope, and a handy light stand for larger subjects. The video camera, which can also capture very nice still photographs, feeds its imaging information to the electronic system topped by the high resolution Sony monitor. Images are then edited and manipulated in the dedicated desktop PC, as indicated here by another old friend, the port entomology identifier, Eric Johnson.

Eric was glad that Mr. Withee was also in the shop that day, because he is the only one who is able to operate the new equipment so far. After a quick introduction to the set-up by Mr. Withee, we proceeded to fire up the new gear to see if we could generate and manipulate some digital imagery.

As luck would have it, within a few minutes a courier arrived with several urgent ID requests from the Portland office. Eric and the urgent samples disappeared into another part of their laboratory, where I subsequently found him going through the samples under an old B&L microscope. The first sample contained a few collembolas (springtails), and the second, some mycetophilids (fungus gnats). Both are common and neither generally considered economic. Eric was not glad to see either one, grumbling about the time involved with the samples and the state of basic entomology knowledge of new line staff. After some discussion, I suggested that he might try to grab a couple quick images of the sample insects and e-mail them off to the officer who sent them as a “training opportunity,” to put the new equipment to work. His reply was that he had neither the time nor the energy.

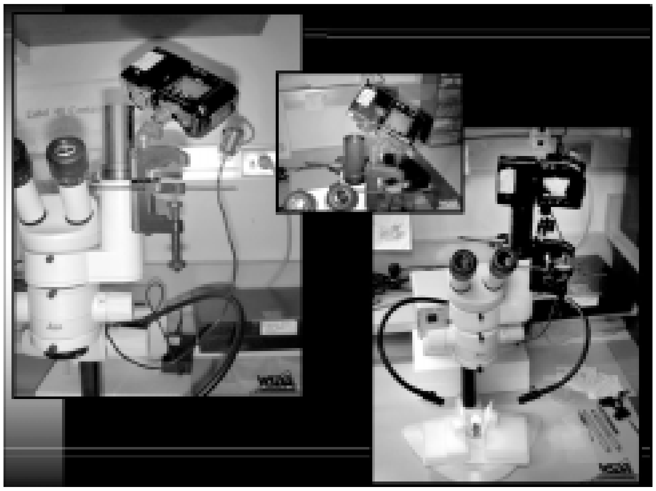
Eric’s predicament reminded me of an earlier time when the new digital technology was a bright light that we expected would reduce our workload by increasing our efficiency, skills, and knowledge. The digital revolution would bring us mind-boggling tools to protect our economy, our environment, and the American way.

In 1990, when this action photo was taken, our budgets may have been headed down the plumbing, but we did have some kind of vision (or hope, at least) that the technology might help. Note the core of my digital arsenal here is a TRS-80 Radioshack “computer” and a LORAN receiver.

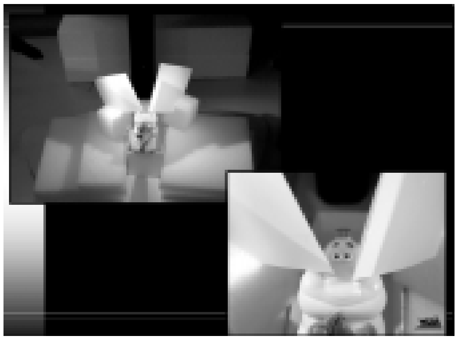
However, sometimes the new technology does not quite work like the visions or TV advertisements. Sometimes the “learning curve” takes one down, or backwards, a little further than expected. This is the mighty dilemma of the technology race, more true now than 10 years ago. Can the soldiers learn to handle the awesome power of the new tools and will the hoped for (visionary) advancement of process ever be realized ... on the other side of the learning curve? Or will the (increasingly expensive) technology advance beyond what we are trying to master BEFORE we even get up from the pavement?

This is the digital imagery center in the Washington State Department of Agriculture, Olympia Entomology Laboratory. The space is efficiently organized around the microscopes and cameras, with diagnostic literature on the shelves to the right, laptop computer access on the left (for database and digital reference files), and the reference collection just out of camera view to the left.

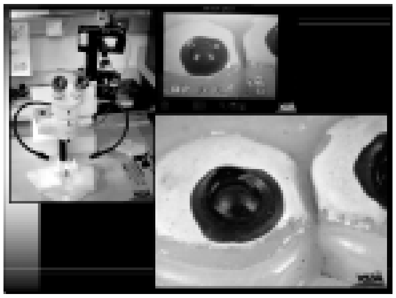
Pictured here are a few of the very inexpensive parts used to mount the CoolPix camera onto the dissecting microscope. The key piece is the portable camera mount with the C-clamp in the base, which is actually a very handy tool for under $20. The other parts necessary to rig the camera to look through the standard C-mount camera-shunt on the Leitz (Wild) dissecting microscope are a couple of small wood-working clamps and a photo-tube adapter with an eyepiece lens inside it.



The photo-tube with eyepiece slips into the standard C-mount on the camera adapter, and the clamps hold the portable camera mount against the barrel of the tube so that it can be adjusted to let the camera look down through the tube. With the clamps and mount adjusted correctly, the camera sits atop the tube and is held nicely in place by the camera mount. This same basic set-up should work anywhere that a portable mount like this can be clamped onto a microscope (compound or dissecting), to hold the camera in position to look through any pathway through which an image can be seen by eye. The only parts purchased for this set-up were the clamps, portable camera mount, and an additional eyepiece lens. The camera adapter on the scope is for a standard (film) camera C-mount, and the tube was from an old Wild microscope camera mount. Total equipment budget for the mount set-up was less than $100.

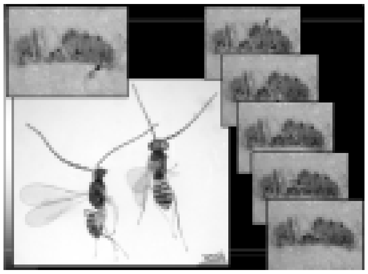


Photomicrography through the dissecting microscope benefits even more from the light diffuser filters than hand-held photography. In this set-up, we want to take pictures of the subject's eyes, so the filters are placed as close as possible to the eyes without getting in the way.

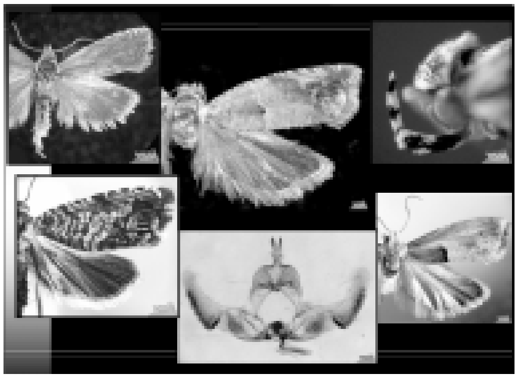


Here is the complete set-up, with the view in the display and the close-up of the eyes. In the full color versions of these pictures there are noticeable color variations between pictures, which are largely the result of illumination by different types of light sources. The microscope and camera shot is by fluorescent light, the camera display is backlit LCD, and the fiber-optic light on the eyes is an incandescent light, color-corrected to match daylight. The Nikon cameras are easily adjusted to compensate for any kind of light color, and, in general, the larger the picture format (the more pixels) the better the overall color matching is with natural colors.

Shown here is another piece of budget-ware equipment that can be very handy for certain applications. A microscope vendor in the Seattle area had a functional base from a defunct microscope that had a fine adjusting stage and a flat top on the scope arm. The camera sits nicely on the arm, and with the camera's autofocus turned off, a three-dimensional specimen can be raised and lowered through the focal plane of the camera, and picture "slices" of various parts of the specimen captured can be "melded" into a single image with the whole three-dimensional specimen in sharp focus. The cost for this hardware is $0.



Another feature of these little Nikon cameras is that they also take small format (640 x 480 pixel) movies at two or three frames per second. Not a high resolution or smooth motion movie, but still a fun and valuable feature, which can be used to show parts of the life cycle of an insect.

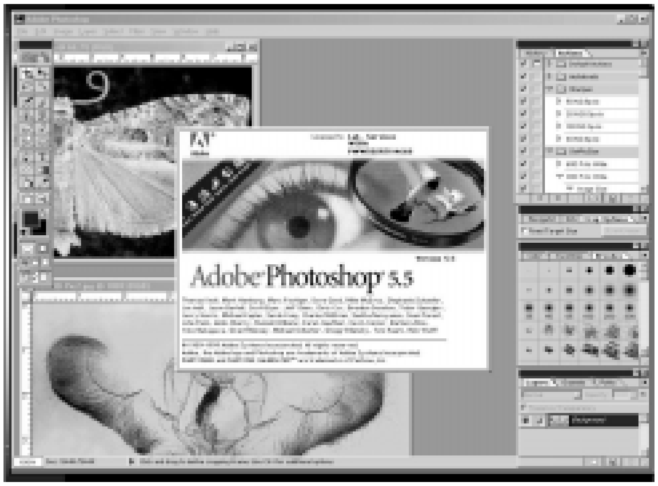


Diagnostic reference graphics have been developed for exotic defoliator surveys in the last few years. At this point, I have many of these types of diagnostic graphics for most of the identified exotic and native species in our reference collection, a total of approximately 130 species. I hope to have a small CAPS project approved for the coming year that will allow me to compile a reference CD with all of the exotic species and many of the native species in our area.

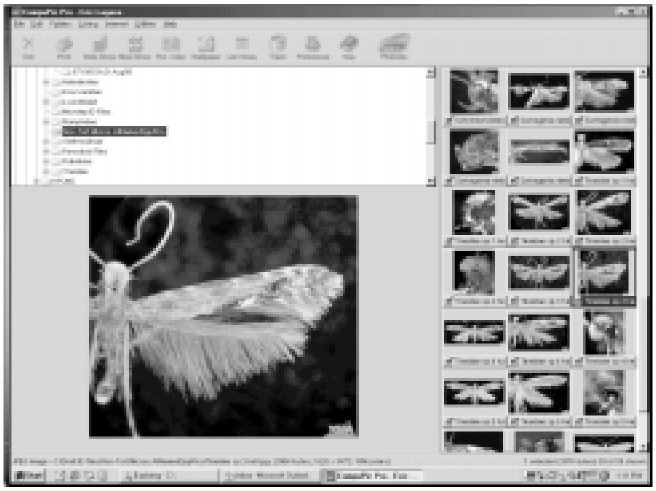
I hope that this introduction to the fun and utility of these new, easy-to-use, high-resolution Nikon cameras has provoked interest. They are sophisticated instruments with fabulous potential for quickly capturing high-quality graphics that can now be immediately shared anywhere the Internet can reach. They also are literally "point-and-shoot" simple on automatic settings, ready to take to the field.

Digital Image Software

There are a couple of pieces of digital image software that should make managing your new graphics library <u>much</u> easier.

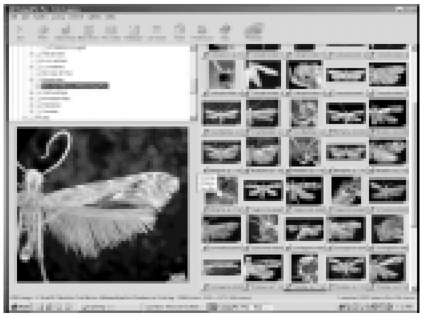


For modifying graphic images, a fairly global consensus is that Adobe Photoshop is the standard. Any conceivable way of modifying a digital picture can be done with Photoshop. Many other graphics software applications will do many things, but not in the manner of Photoshop. Likewise, none of the other graphics modifying applications is as massively intimidating as Photoshop. Actually, there are quite a few applications having intuitive controls that allow sharpening, cropping, and all the other primary functions with graphics, but with a little introduction to Photoshop's controls and automated action palettes, one can appreciate the power and sophistication it has.



The little application pictured here, on the other hand, is software that, in my opinion, is miles ahead of anything else available today for <u>organizing</u> and <u>viewing</u> graphic image files. CompuPic, by Photodex, is a marvelously intuitive and efficient piece of software.

It uses a logical-looking, three-window layout, with standard menu bar and buttons along the top. It has an explorer-like folder-listing window on the top left, a single file-listing window with thumbnails (optional) on the right, and a very nifty preview window on the lower left. Single clicking on the thumbnails on the right pops the graphic up in the preview pane, so that the files can be flipped through (using the arrow keys) to look at them without actually opening them.

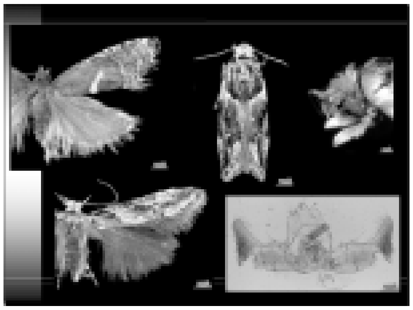


All three windows are scalable by dragging the divider bar.

By scaling up the preview window, the “preview” views are great; even on slower computers, the application to pop up the previews is very fast. Several optional views are selectable for the file listing window.

One listing option has expanded file information details, and another file listing option displays smaller thumbnails as well as expanded file information.

In addition to the file sorting and organization strengths of the application, there are a huge variety of file-modifying functions built in as well. Functions include all the standard changes, as well as some fancy text labeling and batch processing capability. It will even build captioned “picture index” pages in the background to produce hard copy index pages.



CompuPic is really a unique application in many ways and it costs less than $100.

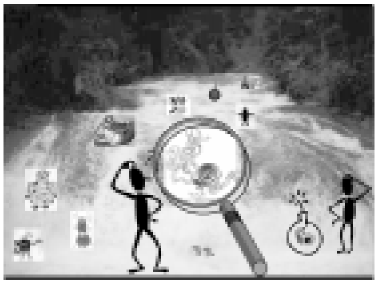
To summarize, the development of the Nikon CoolPix 950 and 990 digital cameras has made high-resolution digital imaging a very practical and powerful tool that has particular utility to the exchange of technical diagnostic information. The rapid, economical capture, sharing, and referencing power inherent in digital imagery should be incorporated into the mechanisms that form the basis of our collective involvement in detecting and monitoring invasive species.

The Future

While this technology brings some exciting and encouraging new facility to the process of identifying potentially significant unknown “new” animals in our midst, I am concerned for the critical mass of systematic expertise that supports the process. I am not sure that there will be experts with whom to consult when the next odd, exotic, walking-fish-moth shows up in a gypsy moth trap in a few years. Expertise among even the major economic insect groups is becoming scarce. I greatly value the support I’ve had recently from the Lepidoptera identification collaborators shown here: John Brown at the Systematic Entomology Laboratory and Michael Sabourin and Bill Miller from the University of Minnesota.

Recently, a friend and compatriot with Agriculture Canada and I were reflecting on the erosion of taxonomic support for quarantine and regulatory surveys (and, in his words, “Forget about other things like biodiversity studies, environmental assessments, and the pure science of classification”). He shared some very disturbing details on this process in Canada. Thirty years ago there were about 40 insect taxonomists and six nematologists working in the Canadian National Collection. Today there are 17 entomologists and no nematologists.

As a biologist, I find it extremely disconcerting that the need for a systematic understanding of the fabric of life we depend on is of less and less importance. In the regulatory realm, how can we promote science-based trade negotiation, create and carry out science-based policies, or even understand the significance of invasive species if that basis continues to be eliminated?



We have come to the uphill reality element of my digitally powered presentation. Sometimes the tides of trade seem like this waterfall. Sometimes just getting through the day seems like this. We could all use a little more power to sort out the important stuff. These exciting new digital cameras are great tools for sharing information.

Use of Spatial Analysis in Disease Investigations

Jerome E. Freier
USDA–APHIS–VS
Centers for Epidemiology and Animal Health
Fort Collins, Colorado 80521

Abstract

Spatial analysis offers a range of investigative methods that can provide valuable insight into understanding pathogen spread within populations of plant or animal species. Before spatial analysis methods are applied, it is best if data are stored in a geographic information system (GIS). GIS is a computer-based technology for collecting, storing, viewing, and analyzing spatially referenced data. GIS methods provide a means of managing and accessing spatial data for use in developing disease surveillance and control strategies. Data stored in a GIS are similar to other data except that geographic coordinates and a unique spatial object identifier are part of each record. In typical systems, spatial data are stored in a graphics file, and unique identifiers link each object to one or more records stored in a separate database file. GIS software processes and interprets location information in either two-dimensional or three-dimensional space. Query operations are used to select either attribute records or specific spatial objects that are then viewed on a computer's display. Critical to the development of a successful GIS is the creation of valid spatial data models and the building of relational data structures. GIS analytical methods can be used to examine the distribution of quantities, determine population densities, provide neighborhood comparisons, and detect changes over space and time.

Spatial analysis, as a function distinct from GIS, is the quantitative study of phenomena located in space and stored in GIS, such as the analysis of point patterns, spatially continuous data, and area data. Specialized, statistical tools are used in spatial analysis to enable the exploratory data analysis (EDA) of spatially referenced information. Point data can be measured in terms of complete spatial randomness (CSR) by evaluating the degree of intensity and spatial interaction among points. Variogram modeling is used to estimate sources of variation between spatial components. Using a variogram model, a continuous surface is created by mathematically interpolating point values to produce a raster model that predicts values between points of known observations. In addition, data associated with areas can be analyzed to determine the correlation of values of the same variable at different spatial locations. Both global and local indicators of spatial association can be derived from polygon data.

GIS combined with spatial analysis can play a valuable role in monitoring plant health and in the development of systems for detecting invasive species. A spatial approach to surveillance will improve disease detection by targeting areas of greatest risk. Specific examples will be presented showing how GIS and spatial analysis methods can be used effectively in a geographically based, invasive species detection system.

Introduction to Spatial Methods

In disease outbreaks, or other types of emergencies, maps play a vital role in orienting field staff members to local conditions and in providing situation managers with a perspective on affected areas (Figure 1). However, the use of maps in disease emergencies is not new. Perhaps the most celebrated example is that of John Snow, a physician working in London in 1854, who demonstrated a spatial association between cholera cases and a single water source. Eliminating public access to the contaminated water supply

Figure 1. *Disease investigators using paper maps to locate study sites.*

brought an end to the outbreak (Brody et al., 2000). Since the time of John Snow, the use of maps by epidemiologists has been a fundamental process in disease investigations. Today we are fortunate to have many specialized methods that make the use of paper maps an outdated approach. The digital world has opened new avenues in the way we look at spatial data.

Mapping is the visual representation of spatial data using cartographic methods and should not be considered synonymous with geographic information systems (GIS). Geographic information systems are a combination of computer technologies that integrate graphic elements, organize information into databases, and compute spatial relationships. The process of mapping generally refers to paper displays, whereas spatial displays on a computer are called views. Although paper maps can be created from data stored in a geographic information system, this format can be difficult to interpret in assessing environmental factors linked to disease transmission. This process can be complicated further when disease data are actively changing relative to environmental factors.

Specialists in many fields use geographic information systems, including emergency services, environmental monitoring agencies, and human health services. In contrast to the popularity of GIS in other fields, plant and animal health uses of GIS have gained rather slow acceptance. The reasons for this are many and varied. One reason is that incorporation of spatial methods works best when users have a specialized knowledge of physical geography, cartography, geodesy, GIS, global positioning systems (GPS), and remote sensing. This is important because spatial methods, such as GIS, are not scientific processes by themselves. Scientific methods, such as assembling ideas, designing investigative studies, collecting and analyzing data, forming working hypotheses, and accepting or rejecting a conceptual hypothesis, are essential to plant and animal studies. Spatial analysis tools should be used in conjunction with scientific methods to validate relationships in the natural world.

GIS Basics

Most disease investigators use an ecological approach in which the interaction between human, cultural activity, and the natural environment is compared to identify causative factors associated with pathogen survival. The term "landscape ecology," first described by Carl Troll, is the science that investigates the relationships between the biosphere and anthroposphere and either the earth's surface or the abiotic components (Vink, 1980; Forman & Godron, 1986; Haines-Young et al., 1993). Landscape ecological concepts are methods to provide the scientific framework for the field of spatial epidemiology.

As shown in Figure 2, GIS methods involve the creation of abstractions of the real world in either two-dimensional or three-dimensional models. In the construction of data models, landscape features are reduced to the simpliest common themes that categorize a feature. Examples of thematic data layers are terrain, soils, vegetation, hydrology, precipitation, demography, transportation, and populated places (Figure 3). It is essential that each data layer be aligned exactly with other data layers such that the real-world coordinates of a geographic location in one layer will be precisely in the same location in all other layers.

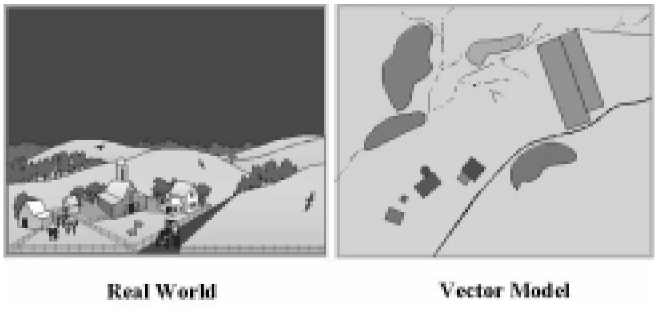


Figure 2. GIS is used to create spatial models of the real world.

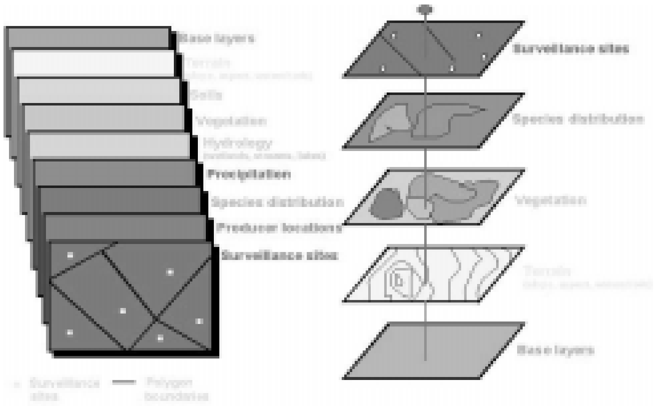


Figure 3. *Example of thematic layers associated with a surveillance study.*

Thematic data layers actually consist of two components: a graphics display and feature attribute data. That is, each feature displayed in a view is linked to an attribute table that contains information relative to that feature. Information about the type of feature, its location, length, and area are stored in the database, along with quantitative or qualitative descriptions. One or more fields should contain a unique identifier and this ID is used to join database tables together, thus extending the information available from basic attributes to specialized data that can be used in analyses.

When new data are used to create GIS database tables, it is essential that new information contains a spatial reference. A spatial reference can be a pair of X–Y coordinates, such as longitude-latitude in decimal degrees or UTM eastings and northings in meters. Geographic boundaries can be used if there is a data layer that will recognize the association between a field in the new data and a field in a theme's attribute table. Common boundary data fields in spatial referencing are state or county boundaries, census tracts, zip code areas, or the Public Land Survey System's Township, Range, and Section grid. Once spatially-referenced data are added as a thematic layer, information can be queried to identify patterns and trends.

One type of theme that serves to orient the user is the base data layer. Typical base data layers include: country outlines, state boundaries, county outlines, township-range-section, rivers and lakes, roads, railroads, cities, or terrain contours. These data layers are readily available from government agencies and commercial data vendors.

There are two categories of GIS data used to represent features in the real world: vector and raster data. In vector data, all feature shapes are defined by X–Y locations in space and each feature is stored as a row in a database table. Vector data use point, line, and polygon objects to model landscape features. Each object contains specific types of information. Points convey information only about location, whereas lines describe length, and polygons contain information about perimeter and area. In an analysis, information about an object's location, length, perimeter, or area can be summarized with other data.

Raster data (Figure 4) are represented as a matrix of cells in continuous space. Generally a raster will be used to represent a single theme; however, the raster format is also associated with image data that may contain large numbers of potential themes. In an analysis, data in individual raster layers are used to create new layers with mathematically-derived cell values. Examples of raster data include satellite images, vegetation classifications, and digital elevation models. In the case of raster data, values are assigned to each cell or pixel. Every cell represents a specific geographic area; therefore, each cell has spatial dimensions and an attribute value. Because raster cells represent specific areas, it is essential that each pixel be registered to real-world coordinates to ensure geographic accuracy with other data layers. In addition, an advantage to raster data is that cells can be organized by either value or type of feature; then the number of cells can be determined. From the number of cells representing a value, or feature class, the area encompassed by that category can be easily calculated.

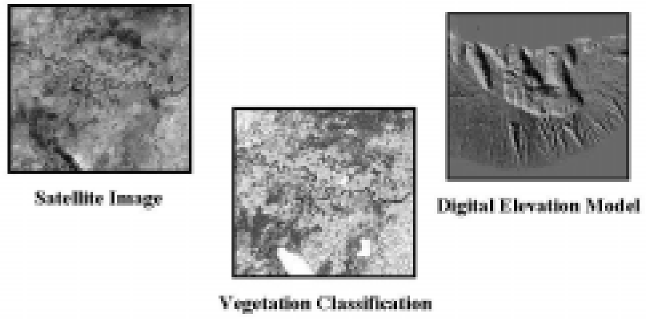

Satellite Image
Vegetation Classification
Digital Elevation Model

Figure 4. *Examples of raster include satellite imagery, the classification of imagery into vegetation classes, or terrain elevation data.*

The concept of topology is a key component of GIS. Topology is the establishment of spatial relationships among points, lines, and polygons. This process involves managing data for each feature object. For example, in terms of topology, a point contains only a pair of X–Y coordinates, a line contains a string of coordinates (vertices), as well as a beginning point (node) and an end. Information conveyed by line data is length and the location of line segments (arcs). Polygon data are similar to line data except that the beginning point and the end are at the same location. Topological information contained in a polygon is perimeter, area, and the location of bounding line segments. After topology has been created in the spatial database, it is then possible to identify spatial associations such as adjacency, containment, and connectivity. Among the most frequently used topological methods is the point-in-polygon process in which the number of points located within a selected polygon boundary is determined by comparing two or more thematic layers.

Another important concept is that of scale. Map scale is the ratio of the distance between two points on a map, or view, and the earth distance between the same two points. A representative fraction (RF) is used to express a map (view) to the real world as a mathematical ratio (e.g., 1:50,000). Generally, three designations of scale are used. Large scale, usually less than 2 x 10^{-5}, means that the RF is a relatively large number, indicating a small area of earth is being considered. Small scale is used to refer to large areas of earth being displayed, where the RF is a relatively small number, usually less than 4 x 10^{-6}. In contrast to map or cartographic scale, geographic scale refers to the spatial extent of a study area. Consequently, large geographic scale covers a large area and small geographic scale represents a small area. It is important to distinguish between map scale and geographic scale when describing an area. The scale at which data will be collected and analyses performed should be determined early in an investigation. The scale chosen should be sufficiently detailed to answer the pertinent scientific questions.

GIS applications work best when data are used in an interactive way. That is, thematic data layers should be selectable and the view updated as new information is added. It should be possible to query either spatial features or the database, while at the same time creating graphs, displaying photographs, and creating map layouts. GIS used in an interactive way allows the user to obtain and manipulate the numbers associated with spatial features. This information can be used for spatial analysis.

Analysis of Spatial Data

Three major functions associated with spatial analysis are visualization, exploratory data analysis, and model building. Each function involves a collection of processes designed to enhance our knowledge about spatial associations. GIS methods are well-suited to presenting data for visualization and interpretation. However, it is important to avoid the "Gee Whiz" effect described by Jacquez (1998). Map layouts can be so visually striking that spatial patterns and associations may seem to appear where none exist. It is important that statistical methods be used to support and evaluate data layers, to formulate testable hypotheses, and to validate spatial associations.

Another concern of data visualization is that this process is too often focused on maps rather than using the full power of spatial data to be represented in three dimensions. According to Limp (2000), it is better to use visual displays that incorporate a wide range of information, stimulating as many human senses as possible.

In exploratory data analysis (EDA), the goals are to identify spatial patterns, especially hot spots of activity. In addition, EDA is used to formulate testable hypotheses and to characterize zones of influence. One cautionary note is that it is important to use care in choosing appropriate statistical methods, particularly with regard to infectious diseases, which may not be independent in terms of space and time. Some basic methods of exploratory data analysis involve characterization of discrete features, continuous phenomena, summarization of data by area, counts, classifications, and density functions.

Discrete, or geographic, feature refers to the exact location of spatial objects. At any given geographic location, a specific feature is either present or not. Point, line, and polygon features can be described based on their location and proximity to other features.

In the case of continuous phenomena, points of known information are interpolated to create a continuous grid of predicted values that covers a specific geographic area. In summarizing data by area, information is associated with specific geographic features then summarized based on that feature. For example, point data showing the location of farms in an area can be summarized according to zip code boundaries, using the point-in-polygon process. After determining the number of points representing farms that fall within each zip code boundary, the zip code areas can be classified according to the number of farms contained within. Another grouping of quantitative data includes counts, amounts, ratios, and ranks. Each type of information can be calculated from the spatial database and the results displayed.

Before displaying quantitative information, it is important to first examine and analyze the numbers being included in a classification series. The most frequently used classifications are: natural breaks, quantiles, equal intervals, and standard deviations. To determine the most appropriate classification method, histogram techniques should be used to characterize the value range and frequency structure of quantitative data. Each classification method will have a significant effect in the display of the end results. Therefore, it is important that the type of classification method used be included in the description of any data analysis.

Dot density maps are used to represent the density of individual locations. Each dot represents a specified number of features at a specific location. For example, a dot might represent 200 moths per trap night. The dots are distributed randomly within each area, such as a county or state boundary. The closer together the dots are, the higher the density of features in that area. The dot density method should be considered as a graphical approach only, rather than as a scientific display of data. It is important to consider that randomly placed dots will give an impression of actual locations, thus leading to a misinterpretation of the data. Consequently, this method is not recommended for use with surveillance or case investigation data.

More advanced methods of exploratory data analysis are used to analyze feature associations (e.g., containment), neighborhoods, spatial clusters, and spatio-temporal changes. A principal objective in spatial analysis is to obtain specific values for selected areas. In the analysis of feature associations, it is desirable to extract the values associated with a specific area within each theme. The values can then be analyzed statistically and used to accept or reject hypotheses. Although the end results of data extraction and analysis procedures are quite valuable, this process is also rather time consuming. On frequently used processes, the extraction and processing of data can be automated through the creation of applidats, small task-oriented programs written for a specific software application. Results of an applidat process can be incorporated into a GIS as a derived data layer.

Points are the most common spatial objects used in disease investigations, and the creation of a buffer around a point is perhaps the simplest level of analysis that can be conducted. Buffers are based on a set-back distance, or radius, and form a polygon boundary around a point. Buffers can be created at various distances from a point to form concentric rings. If buffers are created for several points and the rings overlap, the overlapping areas can be dissolved to form a single buffer polygon. It should also be noted that buffers could be created for lines and polygons.

Another method of creating boundaries around points is the use of polygon fitting techniques. Many of these methods were originally developed to estimate the home range of wildlife, and are currently used to identify centers of activity within a cluster of points. Each method is based on a different algorithm; consequently, the selection of points to be included in a fitted polygon depends on the method chosen and the modeling parameters. Examples of polygon fitting methods are: minimum polygon, harmonic, Fourier, tessellation, minimum convex, and kernel. Choice of method depends on the type of population being sampled and the overall goal. With many of the polygon fitting methods, parameters can be selected that adjust the sensitivity of the model such that increasing limits are placed on the criteria used for point selection.

In the analysis of point clusters, three general categories of spatial statistics are usually applied. These are referred to as global, local, and focused statistics. In the case of global statistics, one or more clusters may occur anywhere in the study area. Local statistics apply if a cluster occurs in specific locations, such as administrative subdivisions within a study area. If locations are pre-specified, then focused statistics are used. Examples of global statistics include: K-function tests, Grimson's method, Cuzick and Edwards tests, the join count, Moran's I, and Geary's C. Specific examples of local statistics include the spatial scan test, LISA statistics, and the geographical analysis machine tests.

Clusters are not always easy to identify, especially if the data are noisy or have a background population that makes groups difficult to distinguish. A major concern of point data is the possible influence of one point on other nearby points. Spatial neighbor analysis procedures are usually applied. One method is to tesselate points to create polygon boundaries around each point. Then spatial autocorrelation indices, such as Moran's I and Geary's C, can be applied to estimate the likely influence of neighboring points on each other.

Another method to analyze spatial point patterns is intensity analysis. This method evaluates the number of points per unit area and expresses a factor that is the intensity of some event.

In examining spatial point patterns, it is important to determine whether an aggregation of points departs from complete spatial randomness (CSR). A frequently used collection of methods used to evaluate CSR is the K-function tests (Ripley, 1976, 1981). The Fhat and Ghat tests indicate the probability of clustering when the distances relative to each statistic are small. Related tests, such as the Khat and Lhat, also plot a calculated statistic relative to distance. However, these tests also include a plot of values expected from a process that simulates values if CSR is occurring. When observed Khat and Lhat values fall outside of the confidence interval of the simulated values, then a point pattern can be considered to be clustered.

Modeling Spatial Data

Spatial data models are based mostly on calculations derived from different data layers in an overlay analysis. Data processed in models are typically in a raster format. However, data in a vector format can be converted to a raster format such that each cell in an enclosed polygon has the value of a specific attribute. Raster cells can be manipulated mathematically, especially through the use of algebraic functions. In addition, Boolean logic schemes can be applied to two or more data layers to include or exclude areas.

Model building begins with the selection of a study area followed by determining the components necessary to produce the final result desired. Components can be weighted according to their level of influence or contribution to the risk of some event. When the model is run, data are automatically brought into the model, converted, edited, and manipulated mathematically to yield the end results.

Another type of modeling is the creation of surface models. Surface models are functional, raster-based surfaces derived from estimates of three-dimensional data by combining geospatial information with a quantitative value (Z), such as elevation, population density, or chemical concentration. Examples of surface modeling methods include: minimum curvature, inverse distance weighted, contouring, profiling, polynomial, triangulation, meshing, and kriging. Each method is aimed at specific applications and the type of method selected should be based on the nature of the data being modeled and the type of output needed.

A popular type of surface modeling is kriging and this method serves as a good example of the underlying methods used to support a model. The first step is to assess variability in the data being modeled using scatter or box plots. The presence and amount of geometric anisotropy in the data should be evaluated using a range of variogram assessments. Afterwards, a variogram model can be constructed of the semivariance in the data. The nugget, sill, and range values are calculated, then used as parameters for the predictive output. The output from a kriging process can take several forms. The most common output formats are contour lines, a raster grid, and scaled, three-dimensional surface. Typically, the output includes both predictive values and standard errors of the predictions. These output models should be examined closely to see whether the data are being properly explained in the results. Output surfaces can be included as a thematic layer in GIS for viewing with other data layers or for further analysis.

The Internet: Bringing Geodata to Everyone

One of the most exciting developments in the past couple of years has been the creation of geodata servers that allow users to access specific information over the Internet. In the case of Internet map servers, data reside on a server, and the client, using an interface viewer, selects specific data to be viewed. The map request can be from a list or from a more sophisticated query of several data layers. Once the map request is completed, it is sent to the server where the appropriate data are assembled and an image file (e.g., a GIF file format) is created and sent back to the client. Depending on the nature of the client-server arrangement, actual data can also be distributed in this way. In some cases, the server-created view can be combined with thematic data layers that the user has on the computer client.

Summary and Conclusions

Use of spatial data in disease investigations requires a suite of methods that may be collectively thought of as spatial data systems. Vector and raster data, including remotely sensed data, are brought into a geographic information system's structure for data storage, maintenance, and retrieval. The key to GIS is in the spatially enabled databases that link vector or raster objects with tabular information. Once information is stored in a GIS, spatial analysis and modeling can utilize these data to describe patterns, test hypotheses and predict trends.

In conclusion, spatial methods require special skills that must be acquired through a fairly rigorous learning process. Geographic information systems provide an excellent means of managing and visualizing spatial data; however, GIS is not necessarily the most efficient way to create maps. Displays of spatial data should be interpreted with caution and skepticism. Be sure to use appropriate analytical methods to explore spatial data before drawing conclusions regarding potential associations. To evaluate the nature of spatial influences, it is best to build models that integrate data from a variety of sources. Finally, the Internet is an ideal way to give spatial data users rapid access to real-time information and make interactive GIS a reality for everyone.

References

Brody, H., M.R. Rip, P. Vinten-Johnson, N. Paneth, S. Rachman. 2000. Map-making and myth-making in Broad Street: The London cholera epidemic, 1854. Lancet, 356:64.88.

Forman, R.T.T. and M. Godron. 1986. Landscape Ecology. John Wiley and Sons, New York, 619 pp.

Haines-Young, R., D.R. Green and S. Cousins. 1993. Landscape Ecology and GIS. Taylor and Francis, London, 288 pp.

Jacquez, G.M. 1998. GIS as an enabling technology. In: GIS and Health, A.C. Gatrell and M. Loytonen (eds.). Taylor and Francis, London, pp. 17–28.

Limp, W.F. 2000. Put the “Fizz” into “Data Viz”. Geoworld 13(9):40–45.

Ripley, B.D. 1976. The second-order analysis of stationary point processes. Journal of Applied Probability 13:255–266.

Ripley, B.D. 1981. Spatial Statistics. John Wiley and Sons, New York.

Vink, A. 1980. Landschapsecologie en Landgebruik. Bohn, Scheltema and Holkema, Utrecht, The Netherlands.

Public Involvement: Creating a Successful Volunteer Program

Marsha B. Riddle
Director of Volunteer Services
Western Carolina Center

Abstract

The framework for the involvement of the public and volunteers in the programs and projects of an organization have been successfully demonstrated in Health and Human Services agencies and organizations for many years, as evidenced by the employment of managers or directors of volunteer services in many of these agencies and organizations.

Specific standards for the involvement of volunteers include: assessing the agency's or organization's need for volunteers and community support; developing recruitment plans and targeting specific individuals and groups for involvement; orientation and training of the public and volunteers to the needs and roles of the organization; and the organization's monitoring, supervising, evaluating, and recognition of volunteers' involvement.

The involvement of volunteers within an organization to support and achieve its goals requires: commitment from the organization and its leaders; time required for planning the program; supervisors willing to involve volunteers in worthwhile efforts that make a difference; time to evaluate efforts and recognize volunteers; and resources to support volunteers' involvement.

Introduction

I reviewed the vision of the Animal and Plant Health Inspection Service in preparing this presentation on public involvement and discovered these statements:

- to bring food to your table
- to stimulate global economics
- to safeguard agricultural resources
- to protect and enhance ecosystems.

Your mission statement "together with our customers and stakeholders, we promote the health of animal and plant resources to facilitate their movement in the global marketplace and ensure abundant agricultural products and services for the U.S. customers" speaks to the organization's commitment to involve the public.

As the professionals in leadership roles, it is up to you to create the mechanisms and opportunities for public involvement. The commitment of the organization to forge partnerships within as well as outside the organization is critical to a successful volunteer program.

A commitment has been made to communicating with stakeholders in your planning process. The job to be done in the global market is much too big for government alone to accomplish. The public must be involved in a more comprehensive and supportive way as partners in your mission.

How you involve the public in achieving your goals, and the steps to creating successful involvement are the focus of this presentation.

Let's begin with the steps necessary for a successful volunteer program.

Planning

Create a volunteer/public involvement advisory committee, whose tasks are to:

- Determine the readiness of the organization to involve volunteers and the climate in which they will be asked to participate.
- Determine the long-range and short-range goals and objectives for their involvement.
- Determine the roles, jobs and opportunities for involvement and participation, including the volunteer qualifications and expectations.

- Determine the support needed for the volunteer program, including supervisory staff.
- Determine orientation and training necessary to the agency and its regulations.
- Establish the rules and guidelines for the volunteer program.
- Determine the budget and resources available to support volunteers.
- Determine reporting, an evaluation to measure impact and involvement.
- Determine a plan to implement the volunteer involvement either by project, state, region, or for the entire organization.

Agencies that want volunteers and public involvement must be able to answer the questions "why have volunteers," "what do we want them to do," and "how will we manage them."

A written statement of philosophy for why the organization is seeking volunteer involvement and written policies and procedures must be in place to support a successful program.

Volunteers within my agency, Western Carolina Center, a state-operated facility for persons with developmental disabilities, include all persons who are non-salaried and perform a service for the organization and/or the individuals whom we serve, including federally funded stipend volunteers such as Americorps and Foster Grandparents who come to us with the support of National & Community Service grants. It also includes Service Learning students, either elementary, high school, college or graduate students, groups and organizations with whom we partner to reach our goals, and parents and friends of those whom we have served by the program.

One additional area of importance is a risk management plan assuring that the organization as well as the volunteer is protected.

The orientation and training plan must prepare the non-paid staff (the volunteer) to do the jobs and assume the roles planned for them.

The financial and personnel resources for the management of the program must include staff:

- to supervise involvement
- to orient and train volunteers
- to evaluate performance
- to recognize participation.

Has a volunteer/public advisory committee or team been appointed for the Animal and Plant Health Inspection Service or the Plant Health Division?

Potential membership of this committee might be:

- staff appointed by leadership
- APHIS alumni organization representatives
- college and university representatives
- local, state, national conservation and preservation representatives of nonprofit organizations
- other concerned stakeholders and customers.

These representatives will come together to plan and to create a volunteer program if asked for their input.

Understanding the Trends and Issues in Volunteerism

Volunteering has changed greatly over the last 25 years. The great expansion of nonprofit organizations has picked up where government (local, state, and national) has decreased services and programs, and has moved forward with supporting the needs of people, the environment, and the community.

Recruiting for volunteers who do not exist in the community is a fruitless and frustrating task. Spending time and energy targeted to the group or individuals who can best meet the identified roles of an agency is the key to a successful recruiting strategy.

The Independent Sector's recently released national survey of giving and volunteering in the U.S. shows that:

- 56% of adults volunteered – the highest ever recorded by their survey
- 109 million people volunteered, representing the equivalent of 9 million full-time employees valued at $225 million
- 90% of people volunteered when asked.

These facts reveal that the number of people who volunteered was up; however, the number of hours they volunteered individually was down. People often prefer short-term involvement, even such activities as "Make a Difference Day" in October, or Youth Service Day in April, or Martin Luther King Day in January.

In a recent publication by the Points of Light Foundation, a national nonprofit organization, several futurists reported their projections to the American Demographics magazine on the volunteer of tomorrow.

- E-power is the power of the future. People are more educated, have more disposable income and are wired and connected. The Internet is used as a premier source for information for decision-making, including how and where people volunteer.

Putting these trends together, we discover that 40% of Americans, aged 50 and over, have home computers, and 70% of those have Internet access. This increases daily. Over two-thirds use the computer for E-mail and over half do research, check out current events, and discover opportunities to buy. Why not opportunities to volunteer as well?

- An immigration boom in the U.S. is similar to that of the 1900s, with today's immigrant population being mostly Hispanic.

- Baby boomers are aging. By 2020, 6.5 million people will be 85 years old or older and the number of retiring baby boomers increases daily.

Are public involvement and volunteer opportunities a part of your web site as well? Several web services can put your organization and its volunteer opportunities on-line. An integrated E-mail makes contacting volunteers easy. Partnerships with academia and other government agencies and organizations can accomplish the same.

There are 26 million young people aged 12–18 in the U.S. or 13% of the adult population. They have grown up in a more diverse and connected world. Their view of the world is drastically different from the baby boomers. Their world of reference:

- had no Atari or record albums
- have never seen a T.V. that stopped at Channel 13
- do not remember the fear of nuclear war.

They are fiercely independent and savvy. This audience straddles both Generation X and Generation Y.

This group of individuals has great potential for supporting causes of concern, but, according to the Independent Sector, in 1998 less than 43% of 18- to 24-year-olds were asked to volunteer. Eighty-seven percent (87%) of the group asked volunteered. Today's youth have no clear common cause to rally around. It could be your cause.

Youth who volunteer do so because they are told of the opportunity, understand why they are needed, have some personal connection to the cause, believe that getting involved will help them benefit personally, and believe they can make a difference in the world.

They believe that a good volunteer experience is rewarding work, will expand their horizons, give them a sense of belonging to the group, provide them with clear communication and understanding of their role, that their input will be honored, and that recognition will be meaningful and personal.

If you want to target youth, offer flexibility, think big, see the opportunities through the eyes of an 18-year-old. Recognize that they need to improve their resumés, may be looking for jobs, and have great personal strengths and abilities often unrecognized because they are young.

Recruitment Strategies

Once your staff team and managers of the volunteer programs have been identified, they will spearhead the marketing and recruitment strategies developed by the advisory committee for the program's projects and jobs created.

Market your opportunities for involvement through the organizations who share your vision and have common goals and concerns, and create national public information and education programs with themes, always reminding the public of the opportunity for their involvement. Your potential partners for marketing include:

- Key stakeholders dedicated to pest detection activities – these should be identified by lead state and federal plant protection officials in each state
- Land grant colleges and universities in each state which will create the service learning and internship programs
- Environmental groups and biodiversity groups on a local, state, national, and international level
- Industrial research organizations
- Corporate community that shares common relationships
- Agricultural extension services and programs
- Public and private educational systems
- Horticulture enthusiasts and link to recognized shows and exhibitions
- Other government entities and national nonprofits that recruit and place volunteers for year-long commitment and short term activities, for example the Corporation for National & Community Service, including Americorps, Vista, and Retired Senior Volunteers Program
- National senior programs with a volunteerism emphasis – AARP (American Association for Retired Persons), SCORE (Senior Corps for Retired Executives), and your alumni organization
- Nonprofits who care about the environment.

Concentric circle recruitment creates a natural flow of volunteers. It is the simple theory that those who already know you and your mission and have a connection are the best and most successful to target for your recruitment campaign.

Managing and Recognizing Involvement

Managing volunteers is no different from managing any other staff member within your organization. They must have a job description, receive the orientation to the agency necessary for all staff, and the training necessary to accomplish the goals of the position. They must have a specific supervisor assigned to them who will monitor their involvement, receive their time and accomplishment records, and counsel or correct any problems that might arise during their involvement with the organization.

Recognizing that the volunteer has needs and supporting those, particularly if they are learning needs, is critical to their satisfaction.

Recognition comes in a variety of ways and is often specific to the individual volunteer. However, it is critical for the leadership and the community to publicly recognize volunteer involvement within the organization. There are hundreds of ways to recognize volunteers, from a “good morning” and “thank you,” to a “job well done.” If the organization and staff want volunteers around and recognize and support them as they do paid staff, then the volunteers will feel the satisfaction and receive the personal rewards necessary for them to continue their involvement in the organization. Involving volunteers as true members of the team is the most important thing staff can do to recognize the value of volunteers.

In summary, the plan of action for volunteer and public involvement is:

- leadership commitment to the involvement of volunteers
- staff commitment to time necessary for planning, recruitment, training, and supervision of volunteers
- agency commitment to financial and personnel resources necessary for the program
- establishment of the policies and procedures, rules and regulations
- creation of a tracking, monitoring system for volunteers
- establishment of evaluation and recognition systems.

If these elements are in place, a volunteer program will thrive within the organization.

Creating a volunteer program that provides challenges to the volunteers, opportunities for support of the organization, and a committed public who will take the initiative to support the organization will improve and enhance the organization as a whole.

The following are senior and teen resources to contact for recruiting volunteers:

www.aarp.org	American Association of Retired Persons (AARP)
www.iesc.org	International Executive Service Corps
www.nrvc.org	National Retiree Volunteer Coalition
www.seniorcorps.org	National Senior Service Corps
www.pointsoflight.org	Points of Lights Foundation
www.voa.org	Volunteers of America
www.bsa.scouting.org	Boy Scouts of America
www.cool2serve.org	Campus Outreach Opportunity League (COOL)
www.gsusa.org	Girl Scouts of the U.S.A.
www.impactonline.org	IMPACT Online
www.nascc.org	National Association of Service and Conservation Corps
www.servenet.org	Youth Service America
www.indepsec.org	Independent Sector
www.volunteermatch.org	Volunteer Match
Public Allies	Phone: 202–822–1188

Population Processes During Establishment and Spread of Invading Species: Implications for Survey and Detection Programs

Andrew Liebhold
USDA Forest Service

Abstract

Three important population processes occur during any biological invasion: arrival, establishment, and spread. Arrival is the process by which individual(s) of the invading organism are transported to their new habitat. Establishment can be considered the opposite of extinction and represents the growth of a newly arrived population sufficient such that extinction is impossible. Spread is the process by which the species expands its range into the new habitat. Because most biological invasions are caused by human activities, these activities are important to understanding the arrival process and the design of detection programs. Establishment is a highly stochastic process and Allee dynamics may be of considerable importance depending upon the life history of the invading species. These characteristics should be incorporated into the timing of responses to positive detection. Population spread is an area of considerable research currently. Early attempts to understand population spread were based upon a simple theory of reaction-diffusion. However, more recent studies indicate that spread often involves two or more forms of stratified dispersal whereby isolated colonies are founded ahead of the expanding population front; these colonies expand and coalesce with the expanding population front. Efforts to monitor spread should incorporate these characteristics.

Introduction

Since the time of Elton's (1958) seminal book on biological invasion, there has been growing attention by ecologists to various aspects of this subject. Because of the tremendous ecological and economic impacts of invasions, this area has drawn the attention of numerous studies focusing on the applied aspects of invasions. But biological invasions also may be considered miniature "ecological experiments" and, therefore, yield new insights into basic problems in ecology (Vitousek et al., 1996). Out of this work has evolved the field of "invasion ecology" that combines the following ecological sub-disciplines: community ecology, population ecology, landscape ecology, animal ecology, and plant ecology. This paper is a general overview of our current state of knowledge on the population ecology of biological invasions.

When considering the population biology of biological invasions, it is possible to recognize three processes underlying all invasions: arrival, establishment, and spread (Dobson & May, 1986) (Table 1). All three phases have been the object of considerable research. These components of the invasion process also are critical to understanding efforts to manage or control invasions: there is a unique correspondence between each stage of the invasion and the strategies for management.

Arrival

For millions of years, the world's biota has evolved in an environment in which the range of individual species was restricted by oceans, mountain ranges, and other barriers to their natural movement. We know that in prehistoric times, the range of many species changed naturally, mostly in response to changes in climate, but these changes were slow and ultimately limited by geographical barriers (Davis, 1987). Over the last century, the rate of new invasions has been increasing continuously (Sailer, 1978; Vitousek et al., 1996). There is little question that the primary reason for this acceleration of invasions is increased human travel and global trade, which have resulted in high rates of accidental transportation of species (e.g., in the ballast of ships) and intentional introductions (e.g., introduced agricultural plant species). Simberloff (1986) noted that patterns of species introductions parallel intercontinental commerce patterns (e.g., most introductions to North America have come from Europe). We also have accelerated the natural rate of biological invasions by

Table 1. The three basic population components of any biological invasion.

Process	Description	Management Approach
Arrival	Transportation of organism to a geographical location outside of its normal range	International quarantine, inspection
Establishment	Population growth to densities such that extinction is impossible due to random change alone	Detection, eradication
Spread	Range expansion	Domestic quarantine, barrier zones (containment)

disturbing habitats. Disturbances do not alter the arrival process but may enhance the establishment of certain species.

The gravity of the problems created by biological invasions was not fully realized until the early 1900s. Before then, most governments had a *laissez faire* attitude about exotic organisms. For example, faya tree, *Myrica faya*, was repeatedly introduced to the Hawai'ian Islands around the turn of the century for the purpose of reforestation (Whiteaker & Gardner, 1992). After it was established extensively, it became clear that this species crowds out native species. It was not until 1912 that the U.S. Congress finally enacted the Domestic Plant Quarantine Act, which gave authority to the U.S. Department of Agriculture to regulate the movement of plant and animal material into and within the United States (Weber, 1930). These and more recent federal quarantine measures were designed to reduce invasions by limiting the arrival process and thus represent a first line of defense.

Establishment

Every seed that falls to the ground does not develop into a reproducing plant. Similarly, many invaders may arrive in a new habitat but few become established. Here we define establishment as the process that results in a population that persists for many generations. Founder populations typically are small and consequently are at great risk of extinction. Generally, the smaller the founder population, the less likely is establishment (MacArthur & Wilson, 1967). It may be possible to identify a "minimum viable population," though establishment is not a deterministic process and in reality the association between population size and establishment is a stochastic[1] relationship. This function reflects many characteristics of the species, such as its intrinsic rate of reproduction, mate location abilities, dispersal, and genetic diversity (Mollison, 1986).

Two population processes are particularly important when considering establishment: demographic stochasticity and environmental stochasticity. We can mathematically represent the generational change in population density as:

$$N_{t+1} = f(N_t) + \varepsilon 1_t + \varepsilon 2_t \qquad (1)$$

where N_t is population density in year t, $f(N_t)$ is a function that encompasses birth and death processes, $\varepsilon 1_t$ is random variation due to demographic stochasticity, and $\varepsilon 2_t$ is variation due to environmental stochasticity. Demographic stochasticity is random variation in population growth due to variation among individuals in birth and death rates. It is different from environmental stochasticity, which is random variation in birth/death due to temporal variation in the habitat. All populations are affected by environmental stochasticity because of ubiquitous temporal variation in the abiotic environment (e.g., weather). But only low-density populations are affected by demographic stochasticity. When densities are high, variation among individuals averages out to near zero and therefore has little effect on changes in population density. But when densities are low, variation among individuals is proportionally more significant and can dramatically affect changes in density at the population level (Kendall, 1998). The fact that demographic stochasticity affects low-density populations and may lead them to extinction has been recognized as an important issue relating to conservation ecology issues (Stacey & Taper, 1992; Lande, 1993), but has been less widely recognized for its importance in the invasion process.

The important result of demographic and environmental stochasticity is that low-density populations (e.g., newly founded invading populations) are particularly prone to extinction purely as a result of this random variation. However, there is a third source of extinction in low-density populations that should be mentioned: Allee dynamics.

When Warder Allee (1931) wrote his text on animal population ecology, he recognized a phenomenon that exists in populations of certain species: low-density populations are affected by a positive relationship between population growth rate and density (inverse

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[1] Stochastic events or parameters are those governed by probability.

density-dependent mortality). The result of this relationship is that low-density populations are driven toward extinction (Figure 1). This phenomenon, termed the “Allee effect”, may result from a multitude of biological mechanisms, e.g., cooperative hunting, predator satiation, and failure to find mates at low densities (Courchamp et al., 1999). The Allee effect has been recognized as critical to understanding patterns of extinction from the perspective of conservation biology (Stephens & Sutherland, 1999), but less is known about its role during biological invasions. Obviously some organisms (e.g., parthenogenetically reproducing aphids) may not exhibit any Allee dynamics but many species (presumably this would include any species that must mate to reproduce) would be expected to exhibit some form of Allee effect at low densities. Hopper and Rousch (1993) used historical data on successes of attempted introductions of varying numbers of individuals of different parasitoid species to show that the successful establishment of these species was explained by Allee dynamics. It is likely that Allee dynamics may be of critical importance to a number of invading species and therefore may be essential to understanding why some species establish more easily than others.

Another population process that affects establishment is dispersal. The ability of an organism to move long distances may enhance its role as an invader from the perspective of arrival and spread. However, from the perspective of establishment, dispersal may, in fact, detract from its ability to invade, because the Allee effect and stochasticity may interact with dispersal in an important manner. We can conclude from the prior discussion that both stochasticity and Allee dynamics may create the existence of a “critical population density threshold” below which establishment is impossible (Figure 1). Obviously, high growth rates allow certain species to exceed such thresholds and overcome these low-density effects. However, dispersal of individuals from their point of recruitment may reverse the effect of population growth and thereby reinforce low-density effects due to stochasticity or Allee effects.

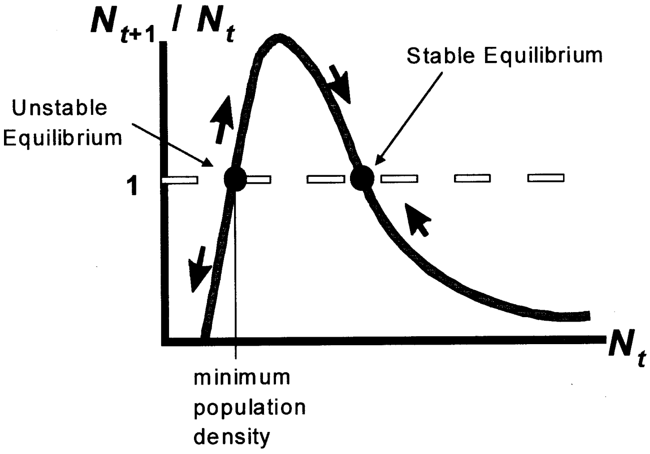

__Figure 1.__ Schematic representation of the Allee effect. Change in population density, N_{t+1}/N_t, is plotted as a function of density at the beginning of the generation, N_t. This relationship determines change in population density f (Nt), shown in equation 1. Note that when density is greater than the minimum population density, it will increase or decrease toward the stable equilibrium, but when it is below this threshold, density will decrease toward extinction.

Understanding this proces has important implications for management. The activity we call “eradication” is aimed at reversing the process of establishment; eradication is forced extinction. It follows from the previous description that eradication is likely to succeed only in situations in which the target population is both low in density and highly restricted in its spatial distribution.

Spread

Once a population is established, its density typically will increase and individuals will disperse into adjoining areas of suitable habitat. For most biological invasions, this spread is the only process that we are able to observe directly; the arrival and establishment phases usually occur without notice by humans. For example, the pine shoot beetle, *Tomicus piniperda*, already was established in six states by the time it was discovered (Haack & McCullough, 1993).

The spread of a species is driven by two processes: population growth and dispersal. As a result most models of population spread have focused on these processes. The simplest and probably the most widely applied model of population spread was developed by Skellam (1951). This model combined Fick’s law of diffusion with an exponential model of population growth.

Fick’s law assumes random movement (diffusion) and states that the concentration, *C*, of particles is normally distributed across any dimension, *x;* thus, the concentration at any point in time after release at point $x = 0$ is described by:

$$Cx,t = \frac{M\, e^{-x^2/4Dt}}{2\sqrt{\pi Dt}} \tag{2}$$

where *t* is the time since the initial release of *M* particles at point $x = 0$ and *D* is the “diffusivity” or “diffusion coefficient” (Okubo, 1980). The diffusion coefficient is constant for any class of particles and set of environmental conditions; *C* is distributed normally at time *t*, with a variance of *Dt*.

The exponential population growth model describes the concept of unlimited population growth:

$$Nt = N_0e^{rt} \qquad (3)$$

where N_t is the number of individuals at time t and r is the "intrinsic rate of natural increase" (birth rate – death rate under optimal condition; i.e., no crowding) (Varley et al., 1973).

Skellam (1951) combined Fick's law of diffusion with the exponential growth model to obtain a generalized model of the spread of an invading organism:

$$Nx,t = \frac{N_{0,0} \quad e^{rt-x^2/4Dt}}{4\pi Dt} \qquad (4)$$

where $N_{x,t}$ is the density of organisms distance, x, from the point of release and time, t, from the time of release of $N_{0,0}$ organisms at time 0. The assumption of random movement in this model implies that the population will spread radially, at an equal rate in all directions (Figure 2A). Skellam (1951) showed that for any detection threshold, T, such that the infested area at any time t is restricted to points where $N_{x,t} > T$, the expansion velocity of the infested front (radial rate of spread), V, is constant and can be described:

$$V = 2 \qquad (5)$$

This model assumes that r and D are constant through time and space during the period of range expansion of the invading organism, an assumption that does not intuitively seem likely (e.g., spatial variation in the habitat may profoundly affect birth/death functions as well as dispersal rates). Nevertheless there has generally been good congruence between predictions of this model and observed rates of spread of most exotic organisms (Levin, 1989; Andow et al., 1990).

Skellam's model assumes a single, continuous form of dispersal and it predicts that range expansion should be a smooth, continuous process (Figure 2A). However some species may be able to disperse in at least two ways. The existence of two forms of dispersal is referred to as "stratified dispersal" (Hengeveld, 1989); in those situations, range expansion will proceed through the formation of multiple discrete, isolated colonies established ahead of the infested front (Shigesada et al., 1995; Shigesada & Kawasaki, 1997). These colonies, in turn, will expand their range and ultimately coalesce. The result of this phenomenon is that range expansion may occur much faster than would occur under a more simple diffusion model.

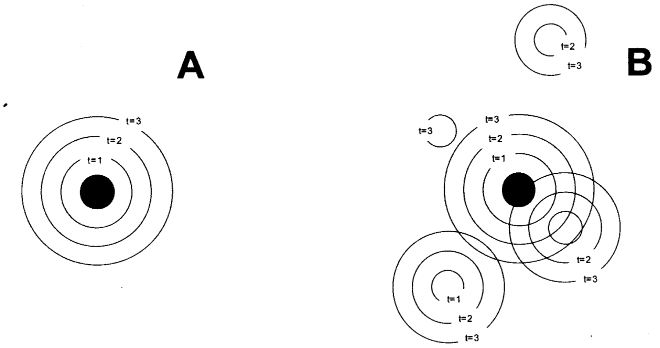

Figure 2. *Schematic representation of range spread between successive generations. The black dot represents the initial range at time 0. A shows spread according Skellam's (1951) diffusion model; B illustrates spread predicted using a stratified dispersal model.*

The contrast between these two models can be illustrated using the gypsy moth, *Lymantria dispar*, as a case study. Liebhold et al. (1992) used estimates of r and D in Skellam's model (equation 5) to estimate the radial rate of range expansion as ca. 2 km/year. The value of D that Liebhold et al. (1992) used was based on the assumption that dispersal only occurs via windborne dispersal of first instars. However Liebhold et al. also reported that over the period 1965–1990 North American gypsy moth populations actually spread at a rate of ca. 21 km/yr, which was much greater than the value predicted using Skellam's model. They concluded that the greater observed rate of spread was due to a second form of dispersal, namely accidental transportation of life stages, and that this stratified dispersal was the cause of the greater spread rates observed. Sharov and Liebhold (1998a) used historical gypsy moth trapping data to identify isolated colonies ahead of the advancing gypsy moth population front (Figure 2B). These data were used to parameterize a stratified dispersal model that predicted the historically observed 21 km/yr rate of spread.

Numerous plant invasive species spread according to a stratified dispersal model (Shigesada & Kawasaki, 1997). An interesting aspect of this type of spread is that establishment is an important component. Isolated colonies are formed ahead of the expanding population front due to dispersal of propagules (Figure 2B), but the ability of these propagules to successfully found new populations that spread and coalesce is entirely dependent upon their ability to establish successfully. Therefore, all of the population processes that are important to establishment, namely stochasticity and Allee dynamics, may be of critical importance to the spread process. For example, the existence of a strong Allee effect will reduce probabilities of establishment, which, in turn, may reduce rates of spread (Lewis & Kareiva, 1993). Studying the historical spread of the house finch in North America, Veit and Lewis (1996) found that mating success in isolated, low-density populations is low and that this results in a strong Allee effect. Veit and Lewis (1996) modeled this effect and showed that Allee dynamics were of critical importance in explaining observed rates of spread.

Implications for Invasion Management Strategies

Understanding the processes operating during the invasion process is critical to virtually all aspects of managing biological invasions. As shown in Table 1, different invasion management activities correspond to each of the three phases of biological invasions. When contemplating different approaches to managing invasions, one should weigh the costs and benefits of concentrating activities at different stages of the invasion process. For example, Sharov and Liebhold (1998b) developed a general bioeconomic model of invasions and illustrated how it can be used to identify an optimal strategy of eradication versus containment. That model used information about rates of spread, costs of eradication, costs of containment, and economic impacts to compare the costs and benefits of eradication versus containment versus no action. Any strategic decision of this type will be highly dependent on the population biology of the organism of interest. Dispersal, population growth rate, stochasticity, and Allee dynamics are likely to influence the selection of a management strategy. For example, if a given species has a relatively high minimum population-density threshold (Figure 1), it may not be necessary to eradicate populations detected at low levels; or if higher densities are detected, eradication may be accomplished simply via suppression to or below that critical density. The combined action of stochasticity and Allee dynamics may accomplish the final act of eradication with no further intervention.

Population biology also should be considered when evaluating the risk of invasion for any species. The probability that a species will successfully invade a new habitat is a function of its ability to arrive, establish, and spread. Some species may be at great risk to one phase of the invasion process, but be at low risk for another phase. For example, tree-killing bark beetles of the genus *Dendroctonus* may be at high risk of arrival in exotic habitats due to their ability to complete development on raw wood, but they are of low risk to establishment because their ability to colonize and reproduce on hosts requires aggregations of large numbers of individuals (a type of Allee effect).

Finally, the population dynamics of an organism may be of critical importance when designing a detection system. As stated earlier, certain species may have a critical density below which stochasticity and/or Allee dynamics drives them to extinction (Figure 1). The relative level of such a threshold should determine the detection threshold that is necessary for a given species. If that threshold is relatively high, detection devices need not be highly sensitive (e.g., light traps, plant volatile-baited traps) and the traps need not be spaced too densely. However, when the critical-density threshold is relatively low, a more sensitive detection system (e.g., sex pheromone baited traps) may be required. In some cases, it may be difficult to obtain and use a species' life-history traits to predict these demographic relationships, but some information usually is available to make these distinctions at a coarse level. These relationships highlight the need to collect more information about the population biology of candidate alien species. Often, little is known about the population ecology of isolated, low-density populations of most species. These considerations underscore the need for additional research.

References

Allee, W.C. 1931. Animal Aggregations. A Study in General Sociology. University of Chicago Press, Chicago.

Andow, D.A., P.M. Kareiva, S.A. Levin and A. Okubo. 1990. Spread of invading organisms. Landscape Ecology 4:177–188.

Courchamp, F., T. Clutton-Brock and B. Grenfell. 1999. Inverse density dependence and the Allee effect. Trends in Ecology and Evolution, 14(10):405–410.

Davis, M.B. 1987. Invasions of forest communities during the holocene: beech and hemlock in the Great Lakes region. Symposium British Ecological Society 26:373–393.

Dobson, A.P. and R.M. May. 1986. Patterns of invasions by pathogens and parasites. In: Ecology of Biological Invasions of North America and Hawaii, H.A. Mooney and J.A. Drake (eds.). Ecological Studies 58. Springer-Verlag, New York, pp. 68–76.

Elton, C.S. 1958. The Ecology of Invasions by Animals and Plants. Methuen, London, 181 pp.

Haack, R.A. and D.G. McCullough. 1993. Update on the pine shoot beetle. Michigan Christmas Tree Journal 36:20–21.

Hengeveld, R. 1989. Dynamics of Biological Invasions. Chapman & Hall, London.

Hopper, K.R. and R.T. Roush. 1993. Mate finding, dispersal, number released, and the success of biological control introductions. Ecological Entomology 18:321–331.

Kendall, B.E. 1998. Estimating the magnitude of environmental stochasticity in survivorship data. Ecological Applications 8:184–193.

Lande, R. 1993. Risks of population extinction from demographic and environmental stochasticity and random catastrophes. American Naturalist 142:911–927.

Levin, S.A. 1989. Analysis of risk for invasions and control programs. In: Biological Invasions: a Global Perspective, J.A. Drake, H.A. Mooney, F. di Castri, R.H. Groves, F.J. Kruger, M. Rejmánek and M. Williamson (eds.). SCOPE 37. Wiley, Chichester, U.K., pp. 425–435.

Lewis M.A. and P. Kareiva. 1993. Allee dynamics and the spread of invading organisms. Theoretical Population Biology 43:141–158.

Liebhold, A.M., J. Halverson and G. Elmes. 1992. Quantitative analysis of the invasion of gypsy moth in North America. Journal of Biogeography 19:513–520.

MacArthur, R.H. and E.O. Wilson. 1967. The Theory of Island Biogeography. Monographs in Population Biology 1. Princeton University Press, Princeton.

Mollison, D. 1986. Modeling biological invasions: chance, explanation, prediction. Philosophical Transactions of the Royal Society of London, Biological Sciences 314:675–693.

Okubo, A. 1980. Diffusion and Ecological Problems: Mathematical Models. Biomathematics 10. Springer-Verlag, Berlin.

Sailer, R.I. 1978. Our immigrant insect fauna. Bulletin of the Entomological Society of America 24:3–11.

Sharov, A.A. and A.M. Liebhold. 1998a. Model of slowing the spread of the gypsy moth (Lepidoptera: Lymantriidae) with a barrier zone. Ecological Applications 8:1170–1179.

Sharov, A.A. and A.M. Liebhold. 1998b. Bioeconomics of managing the spread of exotic pest species with barrier zones. Ecological Applications 8:833–845.

Shigesada, N. and K. Kawasaki. 1997. Biological Invasions: Theory and Practice. Oxford University Press, Oxford, U.K.

Shigesada, N., K. Kawasaki and Y. Takeda. 1995. Modeling stratified diffusion in biological invasions. American Naturalist 146:229–251.

Simberloff, D. 1986. Introduced insects: A biogeographic and systematic perspective. In: Ecology of Biological Invasions of North America and Hawaii, H.A. Mooney and J.A. Drake (eds.). Ecological Studies 58. Springer-Verlag, New York, pp. 3–26.

Skellam, J.G. 1951. Random dispersal in theoretical populations. Biometrika 38:196–218.

Stacey, P.B. and M. Taper. 1992. Environmental variation and the persistence of small populations. Ecological Applications 2:8–29.

Stephens, P.A. and W.J. Sutherland. 1999. Consequences of the Allee effect for behaviour, ecology and conservation. Trends in Ecology and Evolution, 14(10):401–405.

Varley, G.C., G.R. Gradwell and M.P. Hassell. 1973. Insect Population Ecology. University California Press, Berkeley.

Veit, R.R. and M.A. Lewis. 1996. Dispersal, population growth, and the Allee effect: dynamics of the house finch invasion of eastern North America. American Naturalist 148:255–274.

Vitousek, P., C.M. D'Antonio, L. Loope and R. Westbrooks. 1996. Biological invasions as global environmental change. American Scientist 84:468–478.

Weber, G.A. 1930. The Plant Quarantine and Control Administration: Its History, Activities and Organization. Brookings Institute for Government Research Service Monograph of the U.S. Government No. 59. Washington, DC, 198 pp.

Whiteaker, L.D. and D.E. Gardner. 1992. Firetree (*Myrica faya*) distribution in Hawai'i. In: Alien Plant Invasions in Native Ecosystems of Hawaii: Management and Research, C.P. Stone, C.W. Smith and J.T. Tunison (eds.). University of Hawaii Cooperative National Park Research Studies Unit, Honolulu, pp. 225–240.

Presentations

1. Conference Welcome
   "Introduction to the Plant Health Conference on Detecting and Monitoring Invasive Species"
   Charles Schwalbe, Associate Deputy Administrator, USDA, APHIS, PPQ

2. "A History of Adventive Insects in North America: Their Pathways of Entry and Programs for Their Detection"
   Alfred Wheeler, Clemson University & E. Richard Hoebeke, Cornell University

3. "Use of Semiochemicals for Survey and Detection of Exotic Insects: Principles and Constraints"
   Ring T. Cardé, University of California

4. "When 'No' means 'Maybe': Statistical Aspects of Detection Surveys"
   Allan Sawyer, USDA, APHIS

5. "Using Plant Traits to Guide Detection Efforts"
   Sarah Reichard, Research Assistant Professor, University of Washington

6. "Remote Sensing for Invasive Species and Plant Health Monitoring"
   Paul Greenfield, USDA Forest Service, Remote Sensing Applications Center,
   Salt Lake City, Utah

7. "Surveys and Diagnostics 2000: Virtual Cart, Digital Horse and Uphill Reality"
   Eric LaGasa, Chief Entomologist, Pest Program/Laboratory Services Division,
   Washington State Department of Agriculture

8. "Use of Spatial Analysis in Disease Investigations"
   Jerome E. Freier, USDA, APHIS, VS
   Centers for Epidemiology and Animal Health, Fort Collins, Colorado

9. "Public Involvement: Creating a Successful Volunteer Program"
   Marsha Riddle, Western Carolina Center

10. "Population Processes During Establishment and Spread of Invading Species:
    Implications for Survey and Detection Program"
    Andrew Liebhold, USDA Forest Service, Northeastern Research Station, Morgantown, West Virginia

Presenters' List

Ring T. Cardé, Ph.D.
Distinguished Professor andAlfred M. Boyce Chair
Department of Entomology
University of California
Riverside, California 92521
Phone: (909) 787-4492
FAX: (909) 787-3681Email: ring.carde@ucr.edu

Jerome E. Freier
USDA, APHIS, VS
Centers for Epidemiology and Animal Health
555 South Howes Street
Fort Collins, Colorado 80521
Phone: (970) 490-7974
FAX: (970) 490-7999
Email: jerome.e.frier@usda.gov

Paul Greenfield
USDA, Forest Service
Remote Sensing Applications Center
2222 West 2300 South
Salt Lake City, Utah 884119-2020
Phone: (801) 975-3752
FAX: (801) 975-3478
Email: pgreenfield@fs.fed.us

E. Richard Hoebeke
Department of Entomology
Comstock Hall
Cornell University
Ithaca, New York 14853-0901
Phone: (607) 255-6530
FAX: (607) 255-0903
Email: erh2@cornell.edu

Eric LaGasa
Chief Entomologist
Pest Program/Laboratory Services Division
Washington State Department of Agriculture
PO Box 42560
Olympia, Washington 98504-2560
Phone: (360) 902-2063
Email: elagasa@agr.wa.gov

Andrew ("Sandy") Liebhold
USDA Forest Service180 Canfield Street
Morgantown, West Virginia 26505
Phone: (304) 285-1512
FAX: (304) 285-1505
Email: sandy@gypsy.fsl.wvu.edu
http://www.fsl.wvu.edu/~sandy/sandy/sandy.html

Sarah Reichard
Research Assistant Professor
University of Washington
Ecosystem Science Division
Box 354115
Seattle, Washington 98105
Phone: (206) 616-5020 FAX: (206) 685-2692
Email: reichard@u.washington.edu

Marsha Riddle
Director of Volunteer Services
Western Carolina Center
300 Enola Road
Morganton, North Carolina 28655
Email: marsha.riddle@westerncarolinacenter.org

Allan J. Sawyer
USDA, APHIS, PPQ
CPHST - Otis Plant Protection Center
Building 1398
Otis ANGB, Massachusetts 02542-5008
Phone: (508) 563-9303 ext 222 Email:
Alan.J.Sawyer@usda.gov

Alfred G. Wheeler
Department of Entomology
114 Long Hall
Clemson University
Clemson, South Carolina 29634-0365
Email: awhlr@clemson.edu

Organizers' List

Joseph F. Cavey
Entomologist
National Identification Services
Scientific Services
USDA, APHIS, PPQ
4700 River Road, Unit 133
Riverdale, Maryland 20737-1236
Phone: (301) 734-8547
FAX: (301) 734-3602
Email: Joseph.F.Cavey@usda.gov

Kitty Channell
Training Technician
USDA, APHIS, OPD, PDC
7340 Executive Way, Suite A
Frederick, Maryland 21703
Phone: (240) 629-1910
FAX: (301) 663-3240
Email: catherine.a.channell@usda.gov

Mark Dagro
USDA, APHIS, OPD, PDC
7340 Executive Way, Suite A
Frederick, Maryland 21703
Phone: (301) 663-8598 ext 149
FAX: (301) 663-3240
Email: mark.j.dagro@usda.gov

Daniel A. Fieselmann
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, North Carolina 27606
Phone: (919) 513-2126
FAX: (919) 513-1995
Email: Daniel.A.Fieselmann@usda.gov

Tad N. Hardy
Louisiana Department of Agriculture and Forestry
Capitol Station
PO Box 3118
Baton Rouge, Louisiana 70821-3118
Phone: (504) 925-7775
FAX: (504) 925-3760
Email: tad_h@ldaf.state.la.us

E. Richard Hoebeke
Department of Entomology
Comstock Hall
Cornell University
Ithaca, New York 14853-0901
Phone: (607) 255-6530
FAX: (607) 255-0903
Email: erh2@cornell.edu

David Lance
USDA, APHIS, PPQ
Methods Development Center
Building 1398
Otis ANGB, Massachusetts 02542
Phone: (508) 563-9303
FAX: (508) 564-4398
Email: david.r.lance@usda.gov

Vic Mastro
USDA, APHIS, OPD, PDC
Building 1398
Otis ANGB, Massachusetts 02542
Phone: (508) 563-9303
FAX: (508) 564-4398
Email: Vic.Mastro@usda.gov

Van Pichler
Training Specialist
USDA, APHIS, OPD, PDC
7340 Executive Way, Suite A
Frederick, Maryland 21703
Phone: (301) 663-8598 ext 148
FAX: (301) 663-3240
Email: Van.N.Pichler@usda.gov

Charles Schwalbe
Associate Administrator,
Plant Protection and Quarantine
USDA, APHIS
AG Box 3431, Rm. 302-E
Washington, DC 20250
Email: Charles.P.Schwalbe@usda.gov

Participants

Mark Abrahamson
Minnesota Dept. of Agriculture
90 W. Plato Blvd.
St. Paul, MN 55014

Gary Adams
USDA, APHIS, PPQ
1220 Cole Avenue
Helena, MT 59601

Patrick Akers
CA Dept. of Food and Agriculture
1220 N St., Rm. A357
Sacramento, CA 95814

Kathy Allen
USDA, APHIS, LPA
4700 River Road, 4B09
Riverdale, MD 20737

Owen Anderson
North Carolina Wildlife Resources Comm.
20830 Great Smoky Mts. Expressway
Wayneville, NC 28786

Jon Appel
Kansas Department of Agriculture
1711 Westbank Way
Manhattan, KS 66503

Woodward Bailey
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Joel Bard
USDA, APHIS, PPQ
1200 Cherry Brook Drive, Suite 100
Little Rock, AK 72211

O. W. Barnett
NC State University, Plant Pathology
Box 7616
Raleigh, NC 27695

David Bartels
USDA, APHIS, Mission PPC
P.O. Box 2140
Mission, TX 78573

Dick Bean
Maryland Dept. of Agriculture
Plant Protection and Weed Management
50 Harry S. Truman Parkway
Annapolis, MD 21401

Jo-Ann Bentz
USDA, ARS
10300 Baltimore Ave., B–010A, Rm. 238
Beltsville, MD 20705

Lawrence Brown
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Timothy Brown
WV Department of Agriculture
1900 Kanawha Blvd., E.
Charleston, WV 25305

John Byrd
Mississippi State University
Dept. of Plant and Soil Science
Box 9555
Mississippi State, MS 39762

Ring Cardé
University of California
Department of Entomology
Riverside, CA 92521

Joe Cavey
USDA, APHIS, PPQ
4700 River Road, Unit 133
Riverdale, MD 20737

Thomas Chanelli
USDA, APHIS, PPQ
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Kitty Channell
USDA, APHIS, PPQ
Professional Development Center
69 Thomas Johnson Dr., Suite 100
Frederick, MD 21702

Randy Ciurlino
Delaware Dept. of Agriculture
2320 S. DuPont Highway
Dover, DE 19901

Charles Coffman
WV Department of Agriculture
1900 Kanawha Blvd., E.
Charleston, WV 25305

Joe Collins
S-225 Ag. Science Ctr. North
Lexington, KY 40546

Kevin Connors
USDA, APHIS, PPQ
BHW Federal Bldg., Rm. 288
One Federal Drive
Ft. Snelling, MN 55111

Gene Cross
Plant Industry Division/Plant Protection
Section, NC Depart. Of Agriculture
P.O. Box 27647
Raleigh, NC 27611

Thomas Crowe
USDA, APHIS, PPQ
322 Knapp Blvd., S–101
Nashville, TN 37217

Joe Davidson
USDA, APHIS, PPQ
903 San Jacinto Blvd., Suite 270
Austin, TX 78701

Eric Day
Virginia Tech. Dept of Entomology
216 Price Hall
Blacksburg, VA 24061

Thomas Denholm
Division of Plant Industry
New Jersey Dept. of Agriculture
P.O. Box 330
Trenton, NJ 08625

Dana DeWeese
USDA, APHIS, PPQ
P.O. Box 104418
Jefferson City, MO 65110

Keith Douce
University of Georgia
P.O. Box 1209
Tifton, GA 31793

Alan Dowdy
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Paul Dunn
USDA, FS, VMPR
P.O. Box 96090
Washington, DC 20090

Edwin Dyess
MDAC-BPI
P.O. Box 5207
Mississippi State, MS 39762

Donna Ellis
University of Connecticut
Department of Plant Science
U-4163
Storrs, CT 06269

Keith Endres
U.S. EPA
79 T.W. Alexander Drive
RTP, NC 27711

Terry English
USDA, APHIS, PPQ
Oxford Plant Protection Station
901 Hillsboro Street
Oxford, NC 27565

Marvin Felder
USDA, APHIS, PPQ
9600 Two Notch Road, Suite 10
Columbia, SC 29223

Daniel Fieselmann
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Glenn Fowler
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Ste. 2500
Raleigh, NC 27606

Jerry Fowler
USDA, APHIS, PPQ, Eastern Region
920 Main Campus Drive, Suite 200
Raleigh, NC 27606

Larry Fowler
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Joseph Francese
USDA, APHIS, Otis Plant Protection Center
Bldg. 1398, W. Truck Road
Otis ANGB, MA 02542

Jerome Freier
USDA, APHIS, VS
555 South Howes St.
Fort Collins, CO 80521

Gary Gibson
WV Department of Agriculture
1900 Kanawha Blvd., E.
Charleston, WV 25305

William Glenn
Department of Plant Industry
511 Westinghouse Road
Pendleton, SC 29670

Jack Gobin
USDA, APHIS, PPQ
4020 N. Lincoln Blvd., Suite 101
Oklahoma City, OK 73105

Gary Greene
USDA, APHIS, PPQ
654 Munoz Rivera Ave., 7th Fl., Suite 700
Hato Rey, PR 00918

Paul Greenfield
USDA, FS
2222 West 2300 South
Salt Lake City, UT 84119

Teri Hata-Guy
Delaware Department of Agriculture
2320 S. DuPont Highway
Dover, DE 19901

Danny Hamon
USDA, APHIS, PPQ
9550 Micron Ave., Suite F
Sacramento, CA 95827

Carla Handrinos
P.O. Box 3392
Chapel Hill, NC 27515

Vic Harabin
USDA, APHIS, PPQ, Eastern Region
920 Main Campus Drive, Suite 200
Raleigh, NC 27606

Tad Hardy
Louisiana Dept. of Agriculture & Forestry,
Horticulture Division
5825 Florida Blvd.
Baton Rouge, LA 70806

Jeff Head
USDA, APHIS, PPQ
345 Keyway Drive
Jackson, MS 39208

John Bruce Helbig
USDA, APHIS, PPQ
P.O. Box 250
Pierre, SD 57501

Charles Helm
USDA, APHIS
607 E. Peabody
Champaign, IL 61820

David Hirsch
USDA, APHIS, PPQ
3509 Miriam Ave., Suite A
Bismarck, NC 58501

E. Richard Hoebeke
Cornell University
Department of Entomology
Comstock Hall
Ithaca, NY 14853

Craig Hollingsworth
University of Massachusetts
Department of Entomology
Amherst, MA 01003

Gene Holt
USDA, APHIS, PPQ
Ammon Center, 175 Ammon Drive
Manchester, NH 30103

Michael Hosey
U.S. Army Corp of Engineers
P.O. Box 144
Moncure, NC 27559

Participants – continued

Cynthia Huebner
USDA, FS, NE Research Station
180 Canfield Street
Morgantown, WV 26505

Andrea Johnson
1017 Main Campus Dr., Suite 2500
Raleigh, NC 27606

Susan Kostelecky
USDA, APHIS, PPQ
1170 Aycock Dairy Farm Road
Fremont, NC 27830

Susan Kunisaki
USDA, APHIS, PPQ
300 Alamoana Blvd., Rm. 8-152
Honolulu, HI 96850

Eric LaGasa
Pest Program Laboratory Services Div.
Washington State Dept. of Agriculture
P.O. Box 42560
Olympia, WA 42560

Kenneth Lakin
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Dave Lance
USDA, APHIS, Otis Plant Protection Center
Bldg. 1398 W. Truck Rd.
Otis ANG Base, MA 02542

Ronald Lang
USDA, APHIS
1648 South 7th Street, Box 170278
Bozeman, MT 59717

Polly Lehtonen
USDA, APHIS, PPQ
4700 River Road, Unit 133
Riverdale, MD 20737

Andrew “Sandy” Liebhold
USDA, FS
180 Canfield Street
Morgantown, WV 26505

Daisy Ligon
Mitretek Systems, Inc.
7525 Colshire Drive
McLean, VA 22102

Elizabeth Long
Entomology and Plant Pathology
University of Tennessee
P.O. Box 1071, 218 PSB
Knoxville, TN 37901

Victor Mastro
USDA, APHIS, Otis Plant Protection Center
Bldg. 1398, W. Truck Rd.
Otis ANGB, MA 02542

Joseph McLaughlin
Delaware Dept. of Agriculture
2320 S. DuPont Highway
Dover, DE 19901

Michael McManus
USDA, FS
51 Mill Pond Road
Hamden, CT 06514

Robert Meinders
USDA, APHIS, PPQ
600 Fleur Drive
Des Moines, IA 50321

Robert Merrian
154 Montrose
Durham, NC 27707

Leah Millar
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Amy Mize
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Jimmy Moody
USDA, APHIS, PPQ
901 Hillsboro Street
Oxford, NC 27565

Richard Mytkowicz
USDA, APHIS, PPQ
Federal Bldg., Rm. 518
10 Causeway St.
Boston, MA 02222

Participants – continued

Mary Negron
USDA, APHIS, PPQ
320 Mercer Corportate Park
Robbinsville, NJ 08691

Rebecca Norris
USDA, APHIS, PPQ
901 Hillsboro Street
Oxford, NC 27565

Coanne O'Hern
USDA, APHIS, PPQ
4700 River Road, Unit 134
Riverdale, MD 20737

Christian Oseto
Purdue University
Department of Entomology
West Lafayette, IN 47907

David Patterson
NCDA and CS
P.O. Box 27647
Raleigh, NC 27611

Van Pichler
USDA, APHIS, PPQ
Professional Development Center
69 Thomas Johnson Dr., Suite 100
Frederick, MD 21702

Jim Pleasant
USDA, APHIS, PPQ, CAPS
1231 Cumberland Ave., Suite A
West Lafayette, IN 47609

Mark Powell
USDA, OCE, ORACBA
1400 Independence Ave., SW.
Rm. 5248-S
Washington, DC 20250

Mary Megan Quinlan
Suite 17, 24–28 Saint Leonard's Road
Windsor, Berkshire, SL4 3BB, U.K.

Kenneth Rauscher
Pesticide and Plant Pest Management
Michigan Department of Agriculture
P.O. Box 30017
Lansing, MI 48909

Scott Redlin
USDA, APHIS, PPQ
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27606

Sarah Reichard
Ecosystem Science Division & Urban
Horticulture, University of Washington
Box 354115
Seattle, WA 98195

James Rennhack
USDA, APHIS, PPQ
P.O. Box 66192
Chicago, IL 60666

James Reynold
USDA, APHIS, PPQ, Western Region
9580 Micron Ave., Suite I
Sacramento, CA 95827

Nancy Richwine
PA Department of Agriculture
2301 N. Cameron Street
Harrisburg, PA 17110

Marsha Riddle
Director of Volunteer Services
Western Carolina Center Foundation, Inc.
P.O. Box 646
Morganton, NC 28680

Donald Rogers
NC Division of Forest Resources
1616 Mail Service Center
Raleigh, NC 27699

Matthew Royer
USDA, APHIS, PPQ
4700 River Road, Unit 139
Riverdale, MD 20737

Alan Sawyer
USDA, APHIS, PPQ
Otis Plant Protection Center
Bldg. 1398 W. Truck Rd.
Otis ANGB, MA 02542

Robert Schall
USDA, APHIS, PPQ
Professional Development Center
69 Thomas Johnson Drive, Suite 100
Frederick, MD 21702

Participants – continued

James Schoenholz
USDA, APHIS, PPQ
920 Campu Drive, Suite 200
Raleigh, NC 27606

Susan Schouten
Oregon Department of Agriculture
635 Capitol Street, NE
Salem, OR 97301

Charles Schwalbe
USDA, APHIS, PPQ
AG Box 3431, Rm. 302-E
Washington, DC 20250

Anne Selness
Minnesota Dept. of Agriculture
90 W. Plato Blvd.
St. Paul, MN 55107

Ronald Sequeira
USDA, APHIS, PPQ, CPHST
1017 Main Campus Drive, Suite 2500
Raleigh, NC 27602

Bruce Shambaugh
USDA, APHIS, PPQ
3658 E. Chipman Road
Phoenix, AZ 85040

Howard Singletary
717 Powell Drive
Raleigh, NC 27606

Calvin Shuler
USDA, PHIS, PPQ, Eastern Region
920 Main Campus Drive, Suite 200
Raleigh, NC 27606

Suzanne Spencer
NCDAA & CS Plant Industry Division
P.O. Box 27647
Raleigh, NC 27606

William Spitzer
USDA, APHIS, PPQ
4354 Sherwood Forest, Rm. 150
Baton Rouge, LA 70816

John Steward
USDA, APHIS, PPQ
902 Main Campus Drive, Suite 200
Raleigh, NC 27606

Ronald Stinner
1017 Main Campus Drive, Suite 1100
Raleigh, NC 27606

Lisa Tewksbury
University of Rhode Island
Department of Plant Sciences
Kingston, RI 02881

Rober Trickel
NC Division of Forest Resources
2411 Old US 70 West
Clayton, NC 27520

Rober Venette
USDA, APHIS
1980 Folwell Ave., 219 Hodson Hall
University Minnesota
St. Pau, MN 55108

William Wade
USDA, APHIS, PQ
Professional Development Center
69 Thomas Johnson Drive, Suite 100
Frederick, MD 21702

Melody Walker
Wisconsin Dept. of Agriculture
P.O. Box 8911
Madison, WI 53708

Alfred Wheeler, Jr.
Clemson University
Department of Entomology
114 Long Hall
Clemson, SC 29634

Leyinsky Wiscovitch
USDA, APHIS, PPQ
Marina St., Pier 6, 2nd Floor, East Side
San Juan, PR 00901

Scott Wood
USDA, APHIS, PPQ
920 Main Campus, Suite 200
Raleigh, NC 27606

Mitch Yergert
Plant and Insect Section, CDA
700 Kipling Street, Suite 4000
Lakewood, CO 80215