Representing Human-Mediated Pathways in Forest Pest Risk Mapping

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Abstract

Historically, U.S. forests have been invaded by a variety of nonindigenous insects and pathogens. Some of these pests have catastrophically impacted important species over a relatively short timeframe. To curtail future changes of this magnitude, agencies such as the U.S. Department of Agriculture Forest Service have devoted substantial resources to assessing the risks associated with recent or potential forest invaders. These assessments of risk typically include a mapping component; among other things, this presents a useful way to organize early-detection/rapid-response procedures. However, forest pest risk mapping is often limited to readily available and manageable data sets, which results in representations of risk that heavily favor climatic factors or estimates of host species distribution. Detailed examinations of human-mediated pathways of spread are often neglected in forest pest risk analyses owing to a lack of spatial data or uncertainty about a pest's predictive model parameters.

Humans are the most important facilitator of forest pest introduction and spread. With expanding global trade and interstate commerce, the number of potential forest invaders is likely to rise, making the analysis of human-mediated pathways particularly timely. In this synthesis, we present a number of spatial data sources, collected by Federal agencies and private companies for a range of purposes, which can be utilized to represent these human-mediated pathways. Although general in nature, queries can often be used to tailor these data sets to address specific pests. Perhaps, most importantly, the source data can usually be acquired for free or at negligible cost.

Using the sudden oak death pathogen (*Phytophthora ramorum*) and other pests as examples, we illustrate how some of these data sources can be employed for mapping risks associated with human-mediated pathways. First, we demonstrate the use of foreign import cargo statistics—marine, airborne, and transborder—to assess the risk of introduction of new species at United States ports of entry. Second, we examine the utility of inland waterway cargo statistics, freight analysis networks, and other databases on domestic commodity traffic for mapping regional and local spread of forest pests. Third, we explain the diverse applications of business databases, not only to identify clusters of high-risk businesses, but also to rank these businesses using a suite of socioeconomic factors. Finally, we discuss the limited availability of up-to-date land use/landcover data, and present alternative data sources for representing high-risk areas of current urbanization as well as the forest-urban interface.

Whereas many of these data sets are imperfect depictions of human-mediated pathways, integration of several can add significant depth to early-detection/rapid-response projects. To facilitate further applications, we discuss user considerations, future information needs, and potential sources of additional data regarding human-mediated pathways.

Keywords: Commodities, dispersal, forest pests, freight, human-mediated, risk, WUI.

Introduction

In 2000, annual forest losses and control costs in the United States due to nonindigenous forest insects and pathogens were estimated at $4.3 billion (Pimentel and others 2000), and that figure is likely to rise due to the increasing transport of species beyond their native habitats (Brockerhoff and others 2006b). In ecological terms, these pests alter forest composition, structure, and productivity; in some cases, pests basically remove host tree species from forest ecosystems (Brockerhoff and others 2006b, Levine and D'Antonio 2003). A case in point is the once-dominant American chestnut (*Castanea dentata* (Marsh.) Borkh.), which was virtually eliminated from eastern forests by chestnut blight (*Cryphonectria parasitica*) within 50 years of the pathogen's introduction from Asia (Liebhold and others 1995). Over a similar timeframe, the hemlock woolly adelgid (*Adelges tsugae* Amnand) has caused extensive mortality throughout the Northeastern United States and has recently spread into the southern Appalachian Mountains, raising fears that it will decimate both eastern hemlock (*Tsuga canadensis* (L.) Carriere) and Carolina hemlock (*T. caroliniana* Engelm.) populations in the region. Notably, the adelgid was considered a mere nuisance pest of ornamental hemlocks for a few decades after its accidental introduction around 1953, until it began to spread to natural forest stands during the mid-1980s (Souto and others 1996). A related pest, the balsam woolly adelgid (*A. piceae* Rutzeburg), was also accidentally introduced in the latter part of the 20th century, and has removed more than 90 percent of Fraser fir (*Abies fraseri* (Pursh) Poir.) from already sparsely distributed spruce-fir communities in the southern Appalachians (Pimentel and others 2000). In a recent example, the emerald ash borer (*Agrilus plannipennis* Fairmaire) now infests an estimated 40 000 km^2 in the Great Lakes region and Ontario, where it has killed at least 15 million ash (*Fraxinus* spp.) trees and has regularly jumped quarantine boundaries. It is likely that the insect was introduced to the United States 10 or more years before it was first recognized in 2002, during which time populations were able to establish and spread undeterred (US-GAO 2006).

Forest Pest Risk Assessments and Risk Maps

Forest pest risk assessments are intended to provide forest managers with information to prepare for such situations, and in turn, reduce the number of invasive species that become harmful pests (Byers and others 2002). A risk assessment for a particular pest categorizes or quantifies its risk of introduction, establishment, spread if established, and potential economic and environmental impacts (UN-FAO 1995). The spatial representation of such an assessment is a map depicting the varying level of risk of introduction or establishment of a pest throughout a geographic region of interest (Andersen and others 2004b). Risk maps facilitate early-detection/rapid-response procedures by providing a template for the design of regulatory programs and detection surveys or, if a pest has already been established in one part of the geographic area of interest, through control tactics that prioritize areas for which the risk of pest spread is the highest (Andersen and others 2004a).

Importance of Human-Mediated Pathways

Pest risk maps are typically assembled using spatial data from three principal subject areas: host species distribution, environmental factors affecting pest persistence (e.g., climate), and pathways of pest movement (Bartell and Nair 2004). Risk maps often focus on climatic factors or host species distribution or both (e.g., Meentemeyer and others 2004), perhaps because of a lack of information regarding the relevant pathways for a given pest. Nonetheless, human activities—particularly in the area of commercial trade—have received much attention for enabling the spread of invasive pests. Human-mediated pest transport is largely unintentional (Jenkins 1996): forest pests may travel undetected on a variety of materials including wood products, airline baggage, nursery plant stock, solid wood packing materials, hikers' clothing, and passenger vehicles (Campbell 2001, Liebhold and others 2006, McCullough and others 2006, Tkacz 2002, Work and others 2005).

In 2004, a joint workshop by the Society for Risk Analysis Ecological Risk Assessment Specialty Group and the Ecological Society of America Theoretical Ecology Section focused on the standardization of methods for risk assessment as a component of a National Invasive Species Management Plan. Workshop participants noted a critical need for data to represent pathways of introduction of nonindigenous pests that are related to human trade and transport (Andersen and others 2004b). This information need has been echoed by policymakers focused specifically on forest pests (Chornesky and others 2005). For forest pest risk mapping, the challenge is threefold. First, the amount of spatial data specifically collected for forest pests is limited. Second, it can be a challenge to apply available information on pest biology and other fundamental characteristics to the tasks of spatial data mining and interpretation, especially since that fundamental information may be spread across a wide range of journals, government documents, and other literature (Ricciardi and others 2000). Finally, many human-mediated pathways operate on broad (i.e., landscape, regional, national, or even continental) spatial scales, impeding their analysis.

Goals of This Synthesis

During the past couple of years, we have collaborated with scientists from the U.S. Department of Agriculture Forest Service Forest Health Technology Enterprise Team (FHTET), the U.S. Department of Agriculture Animal and Plant Health Inspection Service (APHIS), and other organizations to develop national-scale risk maps for a suite of forest pests. In the process, we have gathered an assortment of data sets for analysis and representation of human-mediated pathways. These data are maintained and updated by Federal agencies, academic institutions, nongovernmental organizations, and, in some cases, private companies for a range of purposes. Many of the data sets are statistical and not explicitly spatial but can be used in combination with more readily available spatial data. Queries can often be used to tailor these data sets to depict spatial patterns or temporal trends, or both, that are relevant for specific forest pests. Perhaps most importantly, the source data can usually be acquired for free or at negligible cost, typically through Internet download. It should be noted that because they are generally not collected with forest pest risk assessment in mind, some of the data sets' characteristics (format, classification scheme, and resolution) limit their straightforward application. Based on our knowledge of human-mediated pathways, we have sometimes adopted simplifying assumptions in order to apply the data sets. Nevertheless, it is our belief that the data significantly improve the forest pest risk assessment process, despite their limitations.

Whereas it is infeasible to create an exhaustive list, in this paper we present an overview of data sets from four categories generally pertaining to human-mediated pathways of forest pest movement:

- Foreign cargo statistical data
- Domestic commodity movement data
- Business data
- Land use/landcover data

For each of these categories, we discuss conceptual linkages between the available data and the depiction of forest pest introduction or spread risk. We describe some specific data sets from each category, highlighting characteristics that should be considered by the potential user. We then illustrate their application using a series of examples related to several current forest pest threats. Finally, to facilitate further applications, we highlight some future information needs and note where researchers may look for additional data regarding human-mediated pathways.

Foreign Cargo Statistical Data

International trade comprised 12 percent of the country's freight tonnage in 1998, and that percentage is expected to double by 2020 (USDOT-FHA 2002b). Many nonnative species are transported to the United States in import cargo shipments. A fairly conservative projection suggests that international trade will result in the establishment of 120 nonnative insects and plant pathogens in the United States between 2000 and 2020 (Levine and D'Antonio 2003). For forest insects, the largest introduction risk seems to be associated with solid wood packing materials (Haack 2003, 2006). Some of these materials may sit unattended in distribution facilities near ports of entry for weeks or more (Campbell 2001). Several nonnative insects now detected in parts of the United States have been regularly associated with solid wood packing materials, including the Mediterranean pine engraver (*Orthotomicus erosus* (Wollaston)) and the sirex woodwasp (*Sirex noctilio* Fabricius) (Haack 2006, Hoebeke and others 2005, Lee and others 2005). Joint risk assessments by APHIS and the Forest Service suggest that the importation of unmanufactured wood, especially in raw log form, is a high-risk pathway of introduction for a diverse range of insects and diseases (Tkacz 2002). The commercial trade of nursery stock and plant materials is another likely pathway of introduction; evidence suggests that the sudden oak death pathogen (*Phytophtnora ramorum*) was likely introduced via the commercial plant trade (Ivors and others 2006).

The Port Interception Network (PIN) database, maintained by APHIS since 1984, provides information on plant pests intercepted at U.S. ports of entry (Work and others

2005). A number of analyses have made use of the PIN database, along with other data sources such as the APHIS Agricultural Quarantine Inspection Monitoring (AQIM) protocol, to analyze trends in the places of origin and commodities most likely to carry nonnative pests, primarily insects (Brockerhoff and others 2006a; Haack 2003, 2006, McCullough and others 2006; Work and others 2005). Although informative, such analyses are constrained by the fact that only 2 percent of cargo is inspected (NRC 2002), and, thus, many pest introductions may go undetected. As an alternative, publicly available statistical data on international trade offer a means to rank the Nation's ports of entry according to forest pest risk. In particular, filtering such data for countries or commodity types of interest or both may reveal ports where the likelihood of intercepting a specific pest is greatest. In addition, certain data sets provide information on eventual inland destinations, facilitating simple but nationwide risk analyses.

A number of government agencies keep databases on some segment of foreign imports to the United States. The associated data are used to generate national reports on current import patterns, as well as changes in those patterns through time. The databases are similar in format; typically, each database record contains fields listing a particular port of entry, a country or region of origin, an import tonnage, and (sometimes) the commodity type. Records can usually be queried and summarized through time to determine the amounts of high-risk cargo arriving from high-risk locations of origin at individual U.S. ports of entry. Readily available coordinate information for these ports can be used to develop maps depicting relative risk of introduction for forest pest(s) of interest.

Foreign Marine Cargo Statistics

In 2001, more than 78 percent of the total U.S. import tonnage was transported on cargo ships (USDOT-BTS 2003). The U.S. Army Corps of Engineers, Navigation Data Center, Waterborne Commerce Statistics Center issues annual summary reports on inbound and outbound foreign marine cargo. The agency also provides public Internet access to statistical data used to generate the reports (USACE-NDC 2006a). Annually compiled data tables are available for 1997 through 2004. Each annual table, available in ASCII or DBASE format, has greater than 100,000 records listing the total weight tonnage of cargo shipments for a specific foreign port (and country) of origin, U.S. destination port, and commodity type. Commodities are classified into one of 41 categories based on the Navigation Data Center's Lock Performance Monitoring System. The U.S. destination ports listed in the tables may be mapped using geographic information systems (GIS) layers provided by the Navigation Data Center or with ports data included in the National Transportation Atlas Databases (USDOT-BTS 2005).

Foreign Air Cargo Statistics

The U.S. Department of Transportation, Bureau of Transportation Statistics publishes monthly commercial air carrier survey information as part of its T-100 databank (USDOT-BTS 2006c). A portion of the T-100 databank focuses specifically on inbound and outbound international flights, listing foreign airport and country, passenger counts, and total pounds of enplaned mail and freight. Currently, ASCII data tables may be downloaded for 1990 through 2005. Unfortunately, freight commodity categories are unspecified in the T-100 databank.

As a possible alternative, the U.S. Department of Transportation, Federal Highway Administration, Office of Freight Management and Operations publishes the Freight Analysis Framework (FAF) database in Microsoft Access format. The FAF compiles data from several sources, including international and domestic waterborne commerce data from the U.S. Army Corps of Engineers as well as the T-100 air cargo data. The most recent version, the FAF^2 database, compiles data from 2002 on freight movement by all transportation modes. Notably, although FAF^2 is intended to supercede the previous FAF^1 database (constructed using 1998 data), a supplementary data table in FAF^1 focuses specifically on international air freight shipments and contains projections of likely freight totals for 2010 and 2020 (USDOT-FHA 2002a). In this supplementary data table, commodities are classified by a two-digit code based on the Standard Transportation Commodity Code system (resulting in 40 categories). The geographic precision of this data table is limited, with shipment destinations reported as States (rather than individual airports) and shipment origins designated only by trade region: Asia, Europe, Latin America, Canada, Mexico, and the rest of the world.

Trans-Border Cargo Statistics

The Bureau of Transportation Statistics publishes land border crossing data collected by the U.S. Department of Homeland Security, Customs and Border Detection Division (USDOT-BTS 2006a). The data detail the total number of loaded and empty truck and rail containers passing through specific United States-Canada and United States-Mexico land border and international ferry crossings. ASCII data tables are available for 1995 through 2004, but as with the T-100 air carrier databank, commodity categories are unspecified. The aforementioned FAF^2 database is perhaps a more useful source, presenting import and export land border crossing data from 2002 in a dedicated table of greater than 200,000 records (USDOT-FHA 2006a). Each record lists a unique combination of origin, destination, border crossing location (sometimes reported as a specific city, but often just a State), the cargo transport mode, the two-digit Standard Classification of Transported Goods commodity category (43 categories), and the total tonnage of that commodity. Origin and destination are reported as Canada, Mexico, or 1 of 114 U.S. metropolitan areas or rest-of-State statistical regions (USDOT-FHA 2006a).

Commodity Coding Systems

A consideration when using the above-described data sets is that any commodity information provided may be of limited specificity. The two FAF databases and the Navigation Data Center's marine cargo statistics all use two-digit commodity codes. A category that might be of specific interest for a forest pest, such as nursery stock, is likely subsumed by a much broader category (e.g., noncereal-grain agricultural products). This may mean that to use the data requires some assumptions, or instead, the use of other data to estimate the breakdown of the broader category. In addition, all of these databases use different commodity coding systems. For example, the Lock Performance Monitoring System, used with the foreign marine cargo data, has a category labeled 41 – forest products, lumber, logs, woodchips. In contrast, the Standard Transportation Commodity Codes, used with the FAF^1 database, include category 24 – lumber and wood products, and the Standard Classification of Transported Goods, used with FAF^2, has two corresponding categories: 25 – logs and other wood in the rough and 26 – wood products. There appears to be movement towards use of the Standard Classification of Transported Goods, which would be beneficial for more sophisticated, multimodal analyses. Documentation for the FAF^2 database includes cross-walk tables for the three commodity coding systems mentioned here (USDOT-FHA 2006b).

Domestic Commodity Movement Data

Human activity enhances the spread of many invasive pests by enabling long-distance dispersal beyond their natural abilities. For instance, insect eggs, larvae, and adults may be accidentally carried on cars or other vehicles, as has been the case with the range expansion of the gypsy moth (*Lymantria dispar* (L.)) in the Eastern United States (Marshall 1981). Perhaps more significantly, domestic shipments of commodities may carry undetected insects and pathogens from ports of entry to previously uninfested locations with favorable conditions. For example, research suggests that the normal spread of the emerald ash borer through local flights has been greatly exacerbated in the Great Lakes region by human transport of infested saplings or firewood (Muirhead and others 2006).

As with the international cargo data, a number of government agencies have developed data sets that track the flow of commercial freight via various transportation modes across the country. These databases may be categorized as either networked or non-networked in structure, depending on whether their focus is on the flow of commodity types or on an arc-node pattern for modeling a particular mode of transport (e.g., freight trucks). The user must consider attribute resolution (i.e., the level to which commodities are specified) and what this allows in terms of filtering and querying the data for application in forest pest risk maps.

Non-Networked Commodity Data

The U.S. Census Bureau and the Bureau of Transportation Statistics jointly issue Commodity Flow Survey reports and an accompanying database as part of a national Economic Census. The most recent iteration of this joint effort was completed using 2002 data (USCB and USDOT-BTS 2005). The Commodity Flow Survey database is a key source of geographically summarized data on the country's domestic commodity movement. The database is delivered with a customized interface that allows data to be filtered for commodity types, transportation modes, distance traveled, and origin and destination regions of interest. Moreover, previous versions (using 1993 and 1997 data) may be downloaded from the Bureau of Transportation Statistics' TranStats data warehouse (USDOT-BTS 2006b), permitting analysis of change through time.

The Commodity Flow Survey 2002 database comprises summary tables for several levels of geographic detail: national, regional; State; and metropolitan area. Significantly, the level of specificity for commodity information reported in a table is tied to the level of geographic detail. Far more specific commodity codes are available for broad-scale (e.g., region-to-region) flows than fine scale (e.g., metro-to-metro) flows. This can be an important issue to consider for pest risk mapping. For instance, *P. ramorum* has been spread to nurseries throughout the United States by infected nursery stock. In the Commodity Flow Survey database, the commodity category "nursery crops and live plants" is only available at a regional scale; finer scale tables use two-digit commodity codes, meaning nursery stock is lumped into an "other agricultural products" category. In such cases, it may be necessary to use ancillary data or combine tables from different spatial detail levels to adjust tonnages accordingly. Moreover, although the list of industries covered by the survey has expanded each time it has been completed, certain industries are generally excluded, including transportation, construction, and some retail industries (USCB and USDOT-BTS 2005). Farms and fisheries are also excluded, meaning that the survey's agricultural commodities data only illustrate shipment from market area to market area, rather than directly capturing areas of commodity production (USCB and USDOT-BTS 2005).

The FAF is a practical alternative to the Commodity Flow Survey database. The FAF^2 database includes a single large table on domestic commodity flow (at the metropolitan area level) that incorporates Commodity Flow Survey data as well as other data sources (e.g., U.S. carload waybill for rail traffic, inland waterborne commerce statistics). The FAF^2 database incorporates these additional sources using a modeling approach; approximately 40 percent of the total commodity tonnage depicted in the FAF^2 domestic commodity table is outside the scope of the Commodity Flow Survey and is thus supplied by the modeling effort (USDOT-FHA 2006c). This adjustment is intended to create consistent nationwide coverage. Nonetheless, it is important to recognize that many of the reported tonnages are model-based estimates, and the degree of error in these estimates is not reported. Commodities are categorized in one of 43 categories (from the Standard Classification of Transported Goods), which is comparable to the level of detail for metro-to-metro flows in the Commodity Flow Survey.

Spatially Explicit Transportation Networks

Spatially explicit networks are regularly used for transportation planning and summary analysis. For example, the Federal Highway Administration's FAF^1 database includes a Highway Truck Volume and Capacity component based on 1998 data, with a similar component for the FAF^2 database due in late 2006 (USDOT-FHA 2002a). The Highway Truck Volume and Capacity component consists of a database table of freight truck traffic flows along major U.S. roadways, which can be linked to corresponding features in a vector GIS road layer. Daily estimates of the number of truck trips along more than 96,000 road segments are calculated programmatically from domestic commodity flow tonnage data (Tang 2006). This permits ranking of road routes most likely to carry trucked freight and the identification of major arteries of interstate freight movement. The network does not include commodity categories, nor have nodes in the network been linked to corresponding populated places or other meaningful locations, although this can generally be addressed using ancillary data sets.

The National Transportation Atlas Databases (NTAD) are a collection of GIS data sets compiled and edited by the Bureau of Transportation Statistics. The most recent version of the NTAD collection was issued in 2005 (USDOT-BTS

2005) and contains two arc-node networked data sets: the National Highway Planning Network and the National Rail Network. The National Highway Planning Network contains greater than 176,000 arcs and 139,000 nodes, whereas the National Rail Network contains greater than 167,000 arcs and 130,000 nodes. Although neither data set contains explicit information on commodity flow along arcs in the network, the nodes are linked to populated places and other meaningful locations (e.g., airports, railyards). In short, these networked data sets depict routes at a fine scale but may need to be linked to commodity information from some other data source to make them useful for assessing broad-scale patterns of forest pest risk.

The U.S. Army Corps of Engineers Navigation Data Center publishes annual Waterborne Commerce Statistics of the U.S. data sets (USACE-NDC 2006b). The annual data sets, spanning the years 1993 to 2004, are broken into four reporting regions: Atlantic, Pacific, Great Lakes, and Mississippi Valley/gulf coast. This is probably the most complete of the networked data sets, providing information on the tonnages of commodities moving along all major inland rivers. Each record in an annual data set has codes for commodity type, direction of traffic (e.g., inbound receiving or outbound shipping), and the specific waterway, which can then be linked to corresponding GIS data. The 146-category commodity coding system is the most elaborate of any of the domestic or international commodity data sets (e.g., five categories for wood products, including fuel wood, wood chips, wood in the rough, lumber, and forest products not elsewhere classified). Nevertheless, it is important to consider that the vast majority of domestic commodity movement is by truck (with rail a distant second), so the networked waterway data may have limited utility for analyzing potential forest pest pathways.

Business Data

Business data sets relevant to the topic of human-mediated pathways fall into two general categories: those that describe general geographic patterns of business activity and those that can be used to pinpoint and analyze individual businesses. The former can be used to describe regional trends in business activities that may increase or decrease forest pest risk. For example, it may be possible to identify geographic areas in the United States with high levels of retail nursery sales, which may be relevant to the risk of introducing a forest pathogen. Unfortunately, such data sets cannot identify specific businesses that may represent key nodes in pest dispersal pathways. It may be useful to identify those key nodes as well as elucidate meaningful spatial patterns in terms of certain of their characteristics (e.g., business location size or sales volume). For example, a large number of retail nurseries in the Eastern United States received *P. ramorum*-infected plants from west coast nurseries during the last few years. Because natural forests around infected nurseries face an elevated risk of potential infection, as do the residential landscapes served by those nurseries, the mapping of specific nursery locations may help determine the best placement of detection survey plots. This is possible using commercially available business location databases.

Table 1—Example of the North American Industrial Classification System

NAICS 2002 code and brief description	
11	Agriculture, forestry, fishing, and hunting
111	Crop production
1114	Greenhouse, nursery, and floriculture production
11141	Food crops grown under cover
111411	Mushroom production
111419	Other food crops grown under cover
11142	Nursery and floriculture production
111421	Nursery and tree production
111422	Floriculture production

An example from the 2002 NAICS coding system, showing the hierarchy of sub-classes related to nursery production within the primary business sector Agriculture, Forestry, Fishing and Hunting (NAICS Code 11).

Industry/Business Classification Systems

There are two primary industry/business classification systems. The North American Industrial Classification System (NAICS) has become the accepted system for the United States, Canada, and Mexico, replacing the older Standard Industrial Classification (SIC) codes (USCB 2006c). Most of the business data sources discussed in subsequent sections use NAICS codes (or both), and cross-walk tables between SIC and NAICS codes are available (USCB 2006c). The NAICS is a hierarchical classification system built upon

20 primary business sectors (USCB 2006c). The system is regularly updated on the same time step as the U.S. Economic Census (described below). The 1997 and 2002 versions of the NAICS have been released, and the 2007 version is in development. A 1,400-page manual describing the classes in the 2002 system is available from the NAICS Web site. Table 1 shows a sample of the hierarchy related to nursery production. Notably, the finest level of detail separates nursery and tree production from floriculture production. Whereas this is more specific than the commodity coding systems described previously, it is still broad in some regards (e.g., not separating nurseries that specialize in trees from those that specialize in shrubs).

General Business Data

The U.S. Census Bureau is a good source of general business patterns data. In particular, the bureau releases an economic census every 5 years, with the most recent version compiled using 2002 data (USCB 2006a). The data are summarized for geographic units as fine-scale as ZIP code areas. Types of information that are available include per-area dollar values of sales, receipts, or shipments for a particular industry class, as well as per-area counts of the number of businesses within a particular industry class. By linking the economic census data to GIS data layers, it is possible to map region-to-region patterns in business activities, and—using information from a previous economic census—to highlight short-term growth or decline in business sectors of interest. Economic census data sets may be downloaded via the Census Bureau's American Fact Finder file transfer protocol interface (USCB 2006b) or are available on DVD-ROMs purchasable by subscription (USCB 2006a).

With respect to the agricultural business sector, the U.S. Department of Agriculture, National Agricultural Statistics Service (NASS) issues summary reports on production of a wide variety of crops, including nursery plants (see the NASS Web site for access to a wide range of reports, http://www.nass.usda.gov/index.asp). Data tables in these summary reports are typically available as ASCII files. Similar to the Commodity Flow Survey, the attribute resolution for a given data table depends on the degree of geographic detail. For example, regarding *P. ramorum*, one might be interested in nursery stock production coming out of California, Oregon, and Washington. A national-scale NASS report on nursery crops lists the total number of producers and sales quantities for 18 States (including the above three States), broken down into specific nursery stock type (e.g., broadleaf evergreens, a category that includes the most significant hosts of *P. ramorum*) (USDA-NASS 2004b). However, the report only details operations with greater than $10,000 in annual sales. In contrast, regularly issued State-level Census of Agriculture reports list the number of all farms that normally have greater than $1,000 in sales, as well as the total greenhouse and open-air acreages per county for broader crop categories such as all nursery stock (e.g., USDA-NASS 2004a). Notably, if a county has just a few operations in a given crop category, greenhouse and open acreages are withheld to protect farmowner privacy.

Business Location Databases

ReferenceUSA is a subscription-based online business database (InfoUSA 2006). Users have access to more than 13 million detailed records on business locations in the United States and Canada. The data were compiled from phone books, business registries, and phone call verifications of individual businesses. Records include fields describing a business's primary industry classification, as well as other industry classes with which it might be associated. Each record has been assigned geographic coordinates. Attribute fields that might be used to sort records include size (square footage), estimated sales volume range, and number of employees. The database may be searched and filtered by location (city, State, ZIP code, and others) or industrial classification codes. Selected records may be downloaded as ASCII files and compiled in statistical software or mapped in GIS software.

Other companies (e.g., Dun & Bradstreet) have developed similar packages, but none are free. Many libraries and government agencies have subscriptions to ReferenceUSA, so at least limited access is available to many users. A related issue that might be of concern to a user is the limitation on the number of records that may be downloaded at one time (the size limitation depends on the paid subscription price). A user must also remember the sometimes-broad scope of industry classifications, and that an individual business may define itself by a number of industry classifications.

Land Use/Land cover Data Sets

The last data category has a loose definition because it involves a wide assortment of data formats and sources. It is beyond the scope of this article to describe all land use/landcover information that may depict some aspect of human activity relevant to pest spread. Instead, we will highlight what we see as two main uses of these data. The first purpose is to map areas that have appropriate conditions to sustain forest pests and that, ultimately, may permit them to spread into naturally forested landscapes. These data sets depict areas where a pest is likely to invade a region and have access to at least a few host individuals. A chief example is spatial data depicting the extent and nature of the forest-urban interface in a given region. The second purpose is to find areas of land use/landcover change owing to human development. The fragmentation or disturbance of natural forests owing to urbanization leads to more chances for forest pest introduction or establishment or both (Chornesky and others 2005). For managing pest risk, it would be preferable to pinpoint areas currently undergoing such changes or facing such changes in the near future. This is a significant challenge, as we discuss below, owing to the timeframe at which most land use/landcover data sets are currently collected and published.

Forest-Developed Interface Data

Landcover maps derived from satellite imagery—such as the U.S. National Land Cover Data (NLCD) (Vogelmann and others 2001)—may be analyzed using moving-window functions (e.g., Riitters and others 2002) to highlight edges between forest and developed landcover types. This may be a straightforward way of identifying interface areas with a high level of pest risk, but it may be even easier to take existing data products and apply them in a forest pest context. For instance, the SILVIS Lab at the University of Wisconsin has created GIS coverages of wildland-urban interface (WUI) for the conterminous United States. The coverages, composed of U.S. Census blocks, distinguish between WUI (where a block contains less than 50 percent wildland vegetation but is within 2.4 km of an area at least 5 km^2 in size with greater than 75 percent wildland vegetation) and intermix (where wildland vegetation occupies greater than 50 percent of a block). SILVIS Lab researchers combined housing density information, landcover percentages derived from 1992 NLCD, and forest proximity measurements to classify blocks into 1 of 13 classes of WUI or intermix. For each block, they calculated the degree of interface/intermix based on both 1990 and 2000 housing density estimates, allowing spatial analyses of changes through time (UW-SILVIS 2006). Although created with a primary focus on fire risk, the WUI data are easily translatable to forest pest risk (Radeloff and others 2005). High levels of intermix may be of particular interest; such intermingling between wildland and residential land may significantly reduce the functional distance between a forest pest and its host species.

Contemporary Land Use/Landcover Change

The wall-to-wall land use/landcover classification provided by the NLCD is sufficient for many analyses. However, remote sensing-derived landcover data sets present some difficulties. In particular, the most recently available complete NLCD coverage dates from 1992, although the 2001 NLCD version is approaching completion. This is because the processing of satellite imagery into classified maps, and subsequent accuracy assessment, is a costly, labor-intensive process. Unfortunately, this means that there will typically be a long time step between subsequent wall-to-wall land use/landcover data sets. This fails to address short-term or recent land use/landcover changes, both of which may be of great interest when assessing forest pest pathways.

As an alternative, it may be possible to use vector GIS data sets that are more regularly updated to depict more recent land use/landcover changes. For instance, many GIS users have access to fine-scale (1:100,000-scale or greater detail) roads data through the Enviromental Systems Research Institute (ESRI) Streetmap extension. These roads data are supplemented versions of U.S. Census Tiger data (ESRI 2005), with new versions of the data issued almost annually. By creating a nationwide grid of cells and intersecting a roads data set with this grid, it is possible to derive an estimate of road density (i.e., the total road length per grid cell). This process can be easily repeated for data sets of any given year, enabling analysis of road density changes. Road density change can serve as an indirect surrogate for areas of general development (i.e., new roads lead to nearby residential and/or commercial construction). This may be an efficient method to highlight areas of increased disturbance owing to construction and areas of potential interaction between pests and hosts.

Application Examples

In the following sections, we detail ways that data for representing human-mediated pathways of forest pest spread have been or may be used for analytical purposes. All of these examples describe ongoing projects, and we would point out that validation or other assessment procedures have not been completed. Although that is an ultimate goal, for now we wish to simply illustrate some of the capabilities of the described data sets and, thus, encourage users to integrate them in additional forest pest risk mapping efforts.

Sirex Woodwasp and Foreign Marine Cargo Statistics

The sirex woodwasp primarily attacks *Pinus* spp. but, occasionally, will attack other conifers in the Pinaceae family. It is a native of Europe, Asia, and northern Africa, where it is rarely a pest. However, it has been accidentally introduced to many parts of the world, resulting in outbreaks in pine plantation forests in Australia, New Zealand, South Africa, and parts of South America (Hoebeke and others 2005). *Sirex noctilio* was intercepted at U.S. ports of entry more than 100 times between 1985 and 2000 (Hoebeke and others 2005). In early 2005, the Forest Service's FHTET organized a team to map the risk of *S. noctilio* introduction and establishment in the United States. An important component of the *S. noctilio* introduction risk map was a ranking of U.S. port locations based on their relative likelihood of receiving cargo carrying the pest. This ranking was constructed using the U.S. Army Corps of Engineers foreign marine cargo statistics database. The database was queried to select records (from all years available at the time, 1997 to 2003) associated with countries with a known or accepted *S. noctilio* presence as well as with commodities that might harbor stowaways of this pest. The commodity categories were selected by consulting APHIS PIN data to identify commodities typically linked to the pest; commonly, these were goods that are associated with wood packaging materials. The resulting map of 151 marine ports (Figure 1) suggests that numerous ports in the Eastern United States face a substantial risk of accidental *S. noctilio* introduction. In particular, several high-risk points of entry in the Southeastern United States are close to large amounts of potential host forest. Notably, a single specimen of *S. noctilio* was found in a trap a short distance from the port of Fulton, New York, about the time this project was undertaken. Subsequent delimiting surveys during summer 2005 detected the pest more than 30 mi inland from the port, and 2006 surveys have detected the pest as far south as Pennsylvania. Surveys for *S. noctilio* in other parts of the United States are ongoing, with the survey design driven by the risk maps developed for this project.

Wood Product Flows From Canada and Mexico Into the United States

Cargo statistics data can also be used to explore risks associated with general pathways rather than specific pests. As an example, in 1998 the Forest Service issued a pest risk assessment regarding the importation of unprocessed *Pinus* and *Abies* logs from Mexico (Tkacz and others 1998). The assessment noted substantial risks of forest pest introduction through wood flows from Mexico. This issue was addressed in recent Federal regulations, which now require treatment of raw wood products from Mexico (USDA-APHIS 2004a). Currently, wood may travel from Canada under a general permit, but with recent restrictions imposed on pine shoot beetle host material (USDA-APHIS 2004b). We used FAF^2 trans-border cargo statistics (from 2002) to map the regional flow of wood products into the United States via land transport from Mexico and Canada (Figure 2). Notably, although "wood products" and "logs and other wood in the rough" are separate commodity categories in the FAF^2 database,

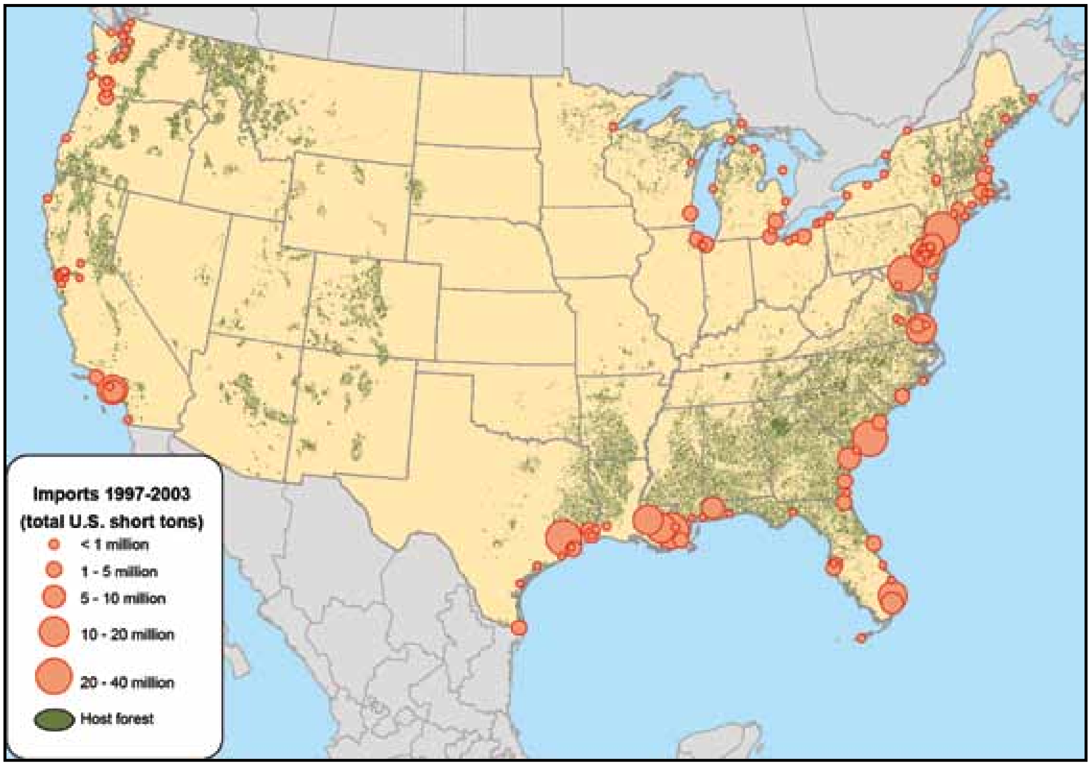

Figure 1—Potential introduction risk of *Sirex noctilio* at U.S. marine ports of entry. Map of U.S. marine ports handling commodities from countries where *S. noctilio* is known or believed to be established. Port locations are scaled in size according to the total tonnage (U.S. short tons) of high-risk commodities received from 1997 to 2003. The background is the distribution of susceptible forest (primarily *Pinus* spp.) in the conterminous United States, generated through spatial interpolation of Forest Inventory and Analysis phase 2 plot data.

they are not distinguished in the border crossing data table. In this simple analysis, Mexico accounts for a very small percentage of total trans-border wood product shipments; however, most States, particularly Texas and California, do receive some volume of Mexican wood products. Most of the Canadian wood products are destined for States just across the border, but some southern metropolitan areas such as Atlanta, Los Angeles, and Houston also receive a large quantity of wood products from Canada.

Truck Traffic Data and Risk of *S. noctilio* Spread Beyond Points of Entry

The example in "Sirex Woodwasp and Foreign Marine Cargo Statistics" described a process for ranking U.S. marine ports of entry according to their relative risk of importing cargo infested by *S. noctilio*. This example builds on that by using spatially explicit transportation network data to predict likely locations of *S. noctilio* spread beyond those initial ports of entry (Figure 3). We employed the FAF[1] Highway Truck Volume and Capacity data to classify U.S. roadway line segments into five classes based on daily truck traffic (roughly 8,000 of the > 96,000 line segments in the network reported no measurable freight traffic). We then defined a set of 96 cities (i.e., urban area polygons defined by the U.S. Census) as ports by tracing the highest-traffic route leaving each marine port of entry point and identifying the first census-designated city along that route. If there were two equally high-traffic routes leaving the port, we selected the first cities encountered along both routes. Naturally, some marine points of entry were located within major urban areas, but a number were geographically distinct, making the tracing of high-traffic routes particularly important. To create a set of potential markets, we intersected the Highway Truck Volume and Capacity data with a coverage depicting census-delineated populated areas. If a polygon in this coverage intersected a

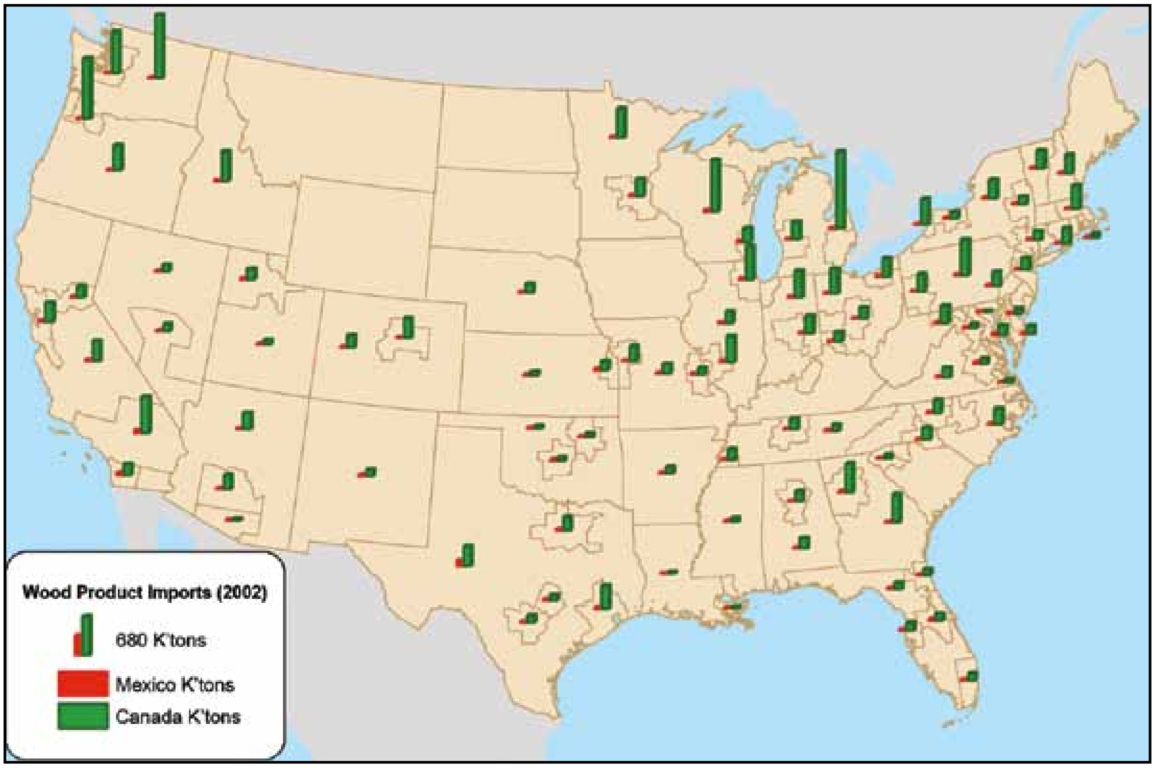

Figure 2—Trans-border wood product flows to United States from Mexico and Canada. Map of 114 metropolitan areas or rest-of-State statistical regions in the conterminous United States. The bar graphs show 2002 wood product imports from Mexico and Canada to each region, reported in thousands of tons.

line segment with a measurable level of truck traffic, then it was incorporated in the final markets layer, which included 2,921 urbanized areas. The port and market layers generated by these analyses, as well as the marine ports data described in "Sirex Woodwasp and Foreign Marine Cargo Statistics," became the primary pieces of the national-scale risk map for *S. noctilio* introduction. As was noted earlier, this map is being used to guide *S. noctilio* detection surveys throughout the country.

Network Model of Nursery Stock Flows

First recognized in the mid-1990s, *P. ramorum* has infected live and red oaks in coastal forests in California and Oregon, with mortality rates of approximately 40 percent (Garbelotto and others 2001, Rizzo and Garbelotto 2003). More critically, the pathogen affects dozens of shrub host species. Many of these shrubs persist after infection and yield large quantities of aerially dispersed spores (Davidson and others 2002, Tooley and others 2004). A number of these shrubs (e.g., rhododendrons, azaleas, camellias) are popular landscaping plants that are often sold as nursery stock (Garbelotto and others 2001, Tooley and others 2004). In the past few years, wholesale nurseries in California, Oregon, and Washington unknowingly shipped hundreds of infected plants to retail outlets in 39 States (Stokstad 2004). Although surveys have not detected *P. ramorum* in natural forests outside the west coast, there is some concern that this pathway may lead to spread of the pathogen from infected nursery stock planted in home landscapes to susceptible forest, of which there is a substantial acreage in the Eastern United States. As already noted, nursery stock is not well represented in the Commodity Flow Survey, so we have adopted an integrated modeling approach to examine the issue of potential *P. ramorum* dispersal via nursery stock. By combining two networked data sets (the FAF^1 Highway Truck Volume and Capacity data and the National Highway Planning Network), we created a nationwide, arc-node GIS infrastructure for dynamic modeling of nursery stock flows (see Figure 4 for regional example). We labeled

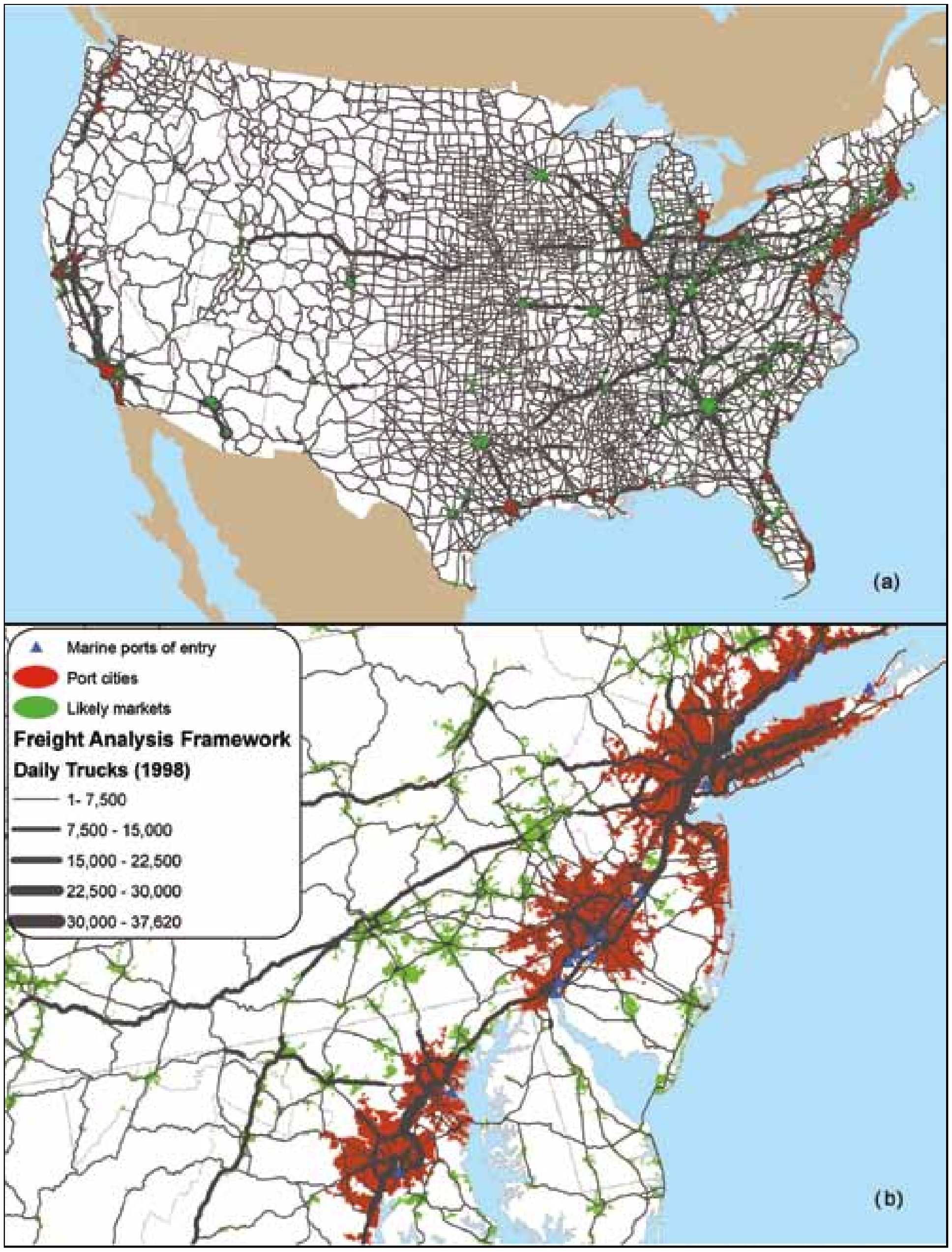

Figure 3—Port and market cities at risk for spread of *Sirex noctilio*. Figure 3a is a map of U.S. urban areas that have a high risk of *S. noctilio* spread. These areas are either port cities or likely markets for imports associated with the pests. Figure 3b is a closeup view of the Washington, DC-New York City corridor, showing roadway routes leaving marine ports of entry, ranked by their volume of truck traffic.

nodes as entry, destination, or transit depending on their roles in the model: nodes in proximity to U.S. wholesale or production nurseries are designated as entry nodes, destination nodes correspond to populated places in the United States, and transit nodes are unweighted link points in the network. We have adopted a Bayesian approach to model probabilities of transmission of *P. ramorum* from entry to destination nodes within the network. For destination nodes, probability of infection is based on the number of plants received from entry nodes as well as the probability that some of the received plants are infected with *P. ramorum*. The number of plants shipped from any entry node is based

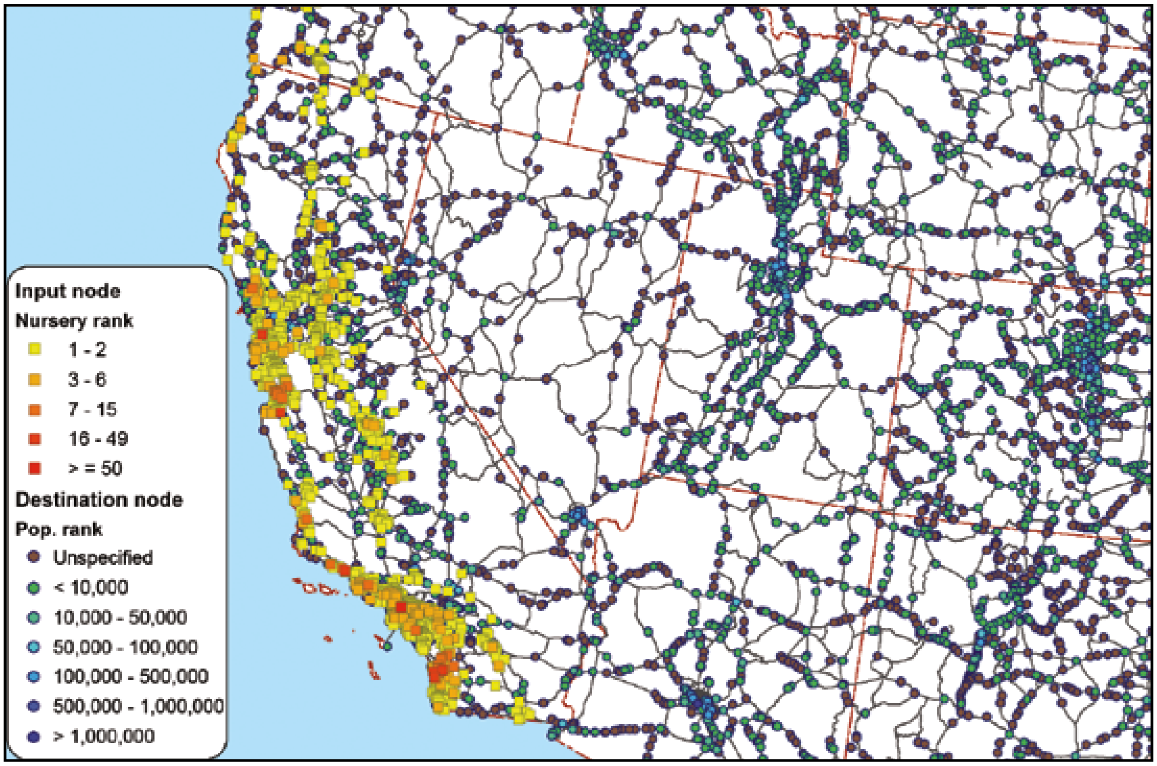

Figure 4—Linear network modeling of *Phytophthora ramorum* spread via nursery stock flows. Regional closeup (California and the Southwestern United States) of a national arc-node network model for predicting potential long-distance dispersal of the *P. ramorum* pathogen on infected nursery stock. The model links wholesale and production nurseries on the west coast to cities and towns throughout the region and the rest of the country. Input nodes are ranked and color-coded by the number of wholesale or production nurseries or both in close proximity. Destination nodes are ranked and color-coded by U.S. Census population.

on the number of nurseries in proximity and the likely volume of outgoing nursery stock, calculated from the U.S. Commodity Flow Survey, the FAF^2 database, and NASS reports on county-level nursery production (described in more detail in “General Business Data”). The probability that some plants received at a given destination node are infected with *P. ramorum* is calculated from infection rates observed in trace forward data (i.e., inspections of plants shipped from known infected production nurseries to retail outlets), and trace back data (i.e., determination of the source of plants found infected at retail outlets) collected by APHIS. Probabilities are also modified by factors affecting how much nursery stock is sold and planted in a given area (e.g., U.S. Census population). We believe the network modeling framework, when completed, will be general enough that it should be applicable for a variety of commodity flow analyses relevant to forest pest risk.

P. ramorum and Production Nurseries

Production nurseries present a higher risk of infecting nearby forests than retail nursery outlets due to several factors: large quantities of stock grown onsite; artificially high moisture levels conducive to the pathogen; and disproportionately large amounts of interface with natural forests. We queried the Reference USA database for all businesses with nursery and tree production as their primary industry classification. This query yielded more than 6,500 business locations nationwide. We ranked the selected businesses into four classes based on their total square footage (from the Reference USA database) and mapped them in relation to overstory host species distribution, represented in the example by a surface depicting the forest percentage of red oak, live oak, or both calculated from Forest Inventory and Analysis data. Figure 5 shows a subset of the nationwide coverage that includes the States of North Carolina and

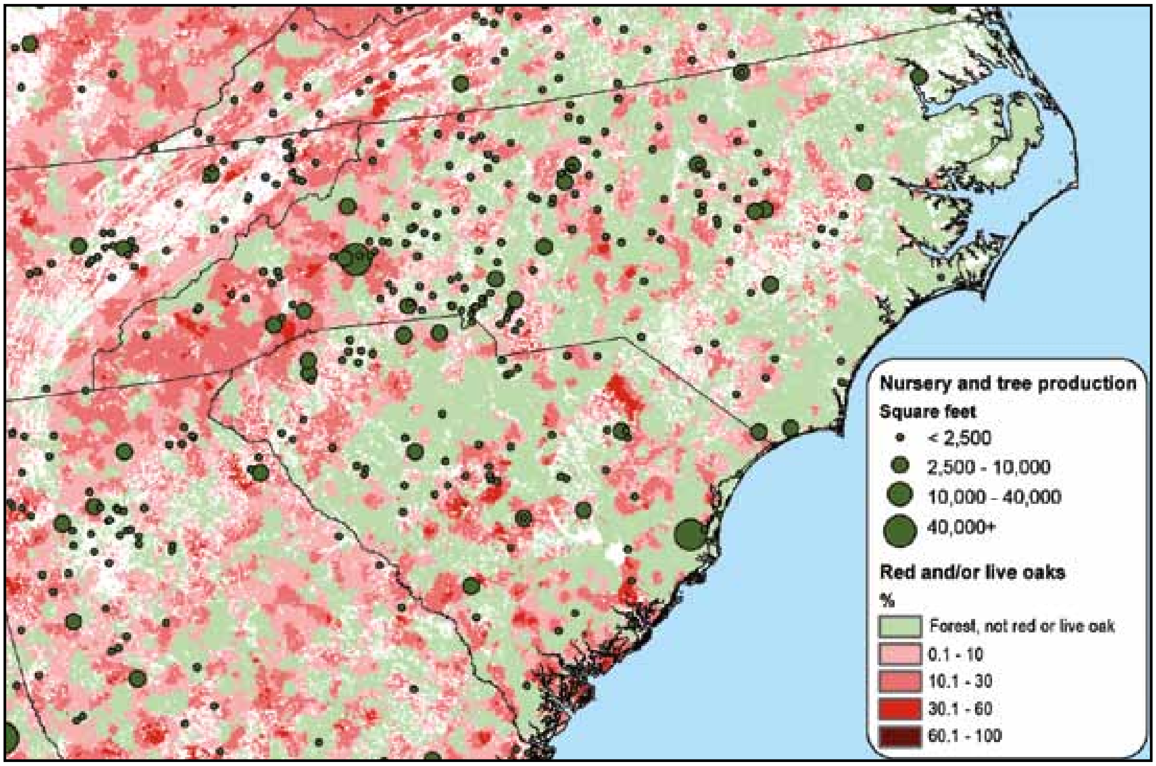

Figure 5—Geographic relationship between production nurseries and *Phytophthora ramorum* host distribution in North Carolina and South Carolina. Map of production nurseries in North Carolina and South Carolina ranked by size class (in square footage). Backdrop map shows overstory red oak or live oak distribution or both.

South Carolina. Larger production nurseries seem to be associated with areas of moderate oak distribution. Whereas this may just be a geographic anomaly, it indicates the kinds of analyses that are possible using specific business location data from ReferenceUSA or similar resource. The production nurseries data generated from ReferenceUSA will be incorporated in a refined version of a preliminary *P. ramorum* risk map developed by the U.S. Department of Agriculture Forest Service (USDA-FS 2004).

Wildland-Urban Interface Data and Areas at Risk for *P. ramorum* Introduction

We used WUI coverages developed by the SILVIS Lab to examine spatial patterns of potential residential-to-forest landscape spread risk for *P. ramorum*. We focused our analysis on an 11-State region encompassing the areas in the Eastern United States that were identified as high risk for *P. ramorum* introduction or establishment or both in the Forest Service's preliminary risk map (USDA-FS 2004). We combined the individual State coverages into a single map and converted this map to a grid format (1-km^2 cells). We then reclassified the 13 original WUI coverage classes into 5 classes: little or no intermix, low intermix, moderate intermix, high intermix, and very high intermix. (Areas labeled as "interface" in the original WUI coverages were classified as somewhat lower risk than intermix areas—see "Forest-Developed Interface Data"). We examined changes in the intermix pattern between 1990 and 2000. Our reclassified maps (Figure 6) depict an expansion of low intermix into new areas at the rural fringes of metropolitan areas, as well as a subtle, but significant, increase in intermix in many suburban areas, particularly along the interstate highway corridor from Atlanta to northern Virginia. Whereas all areas with intermix face some *P. ramorum* risk, areas with greater than a one-class increase between 1990 and 2000 may be of most immediate concern; such areas appear to be widely scattered across the entire 11-State region. As with the production nurseries data, some form of the WUI

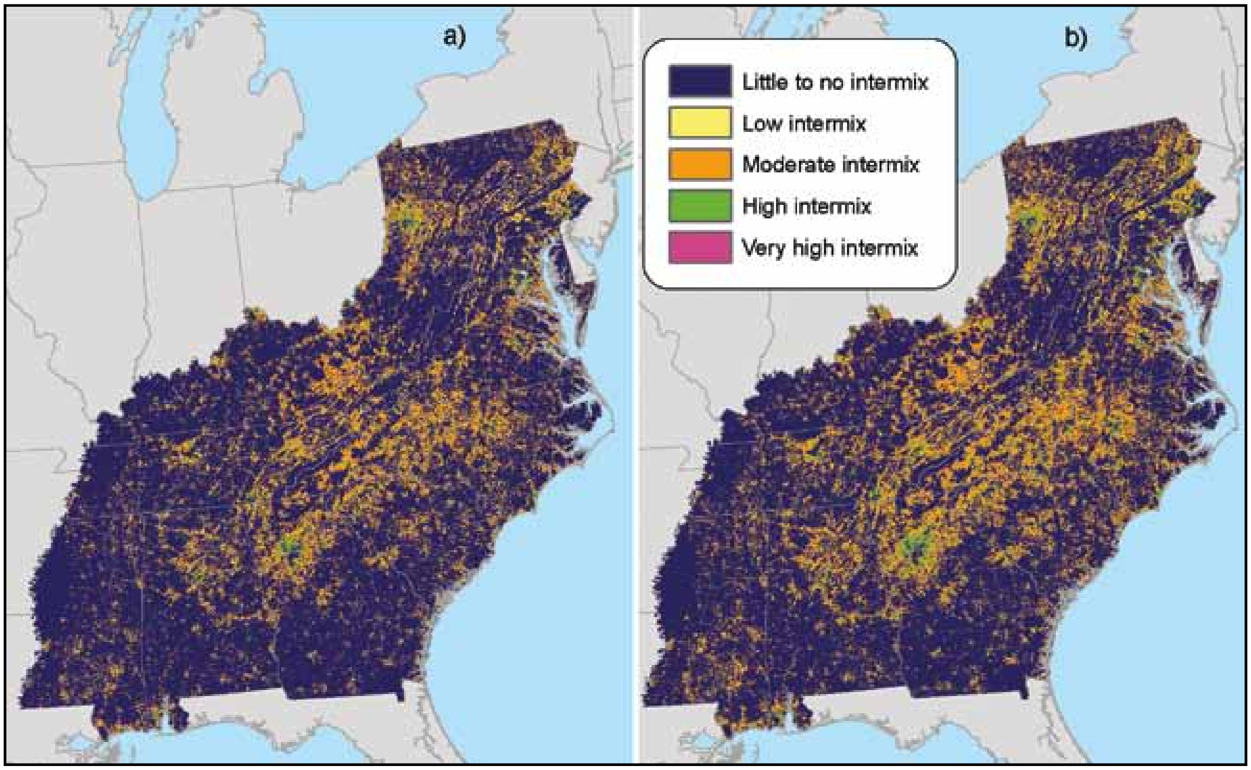

Figure 6—Wildland-urban intermix in an 11-State region, 1990 and 2000. Raster maps (1 km^2 resolution) for 1990 (Figure 6a) and 2000 (Figure 6b), depicting the distribution of five wildland-urban intermix levels (from little to very high intermix) across 11 States in the Southeastern and mid-Atlantic regions.

data will be utilized for the refined version of the Forest Service's national *P. ramorum* risk map (USDA-FS 2004).

Road Density Change and Increased *P. ramorum* Risk

A major concern for the refined *P. ramorum* risk map is identification of areas that may receive large quantities of nursery plant stock that are potentially infected by the pathogen. As noted previously, areas of new residential or commercial development or both are strong candidates as potential introduction sites for *P. ramorum*. As an indirect measure of areas recently or currently undergoing such development, we calculated road densities (total length of all road segments within a cell) for a nationwide grid of 4-km^2 cells using ESRI roads data for 1995, 2003, and 2004. We then calculated road density changes by subtracting the 1995 and 2003 road densities from the 2004 road density for each cell and mapped these changes in relationship to U.S. urban areas. Figure 7 shows a subset of the national maps, focusing on the Research Triangle region of North Carolina. For this subset, the areas with the greatest road density change between 1995 and 2004 do correspond, at least anecdotally, with areas that underwent substantial urbanization during this time period. The 2003 through 2004 difference image also seems to accurately depict areas of recent construction, although the image may highlight major roadwork and not necessarily current residential or commercial expansion, both of which are likely to occur in these areas in the future.

Final Considerations

One of our goals with this synthesis was to provide examples that would stimulate discussion and the interest of other researchers in looking for ways to represent human-mediated pathways in forest pest risk mapping efforts. Although there is widespread awareness that humans contribute to the spread of nonnative pests, there has not been much attention paid to this issue in a spatial analysis

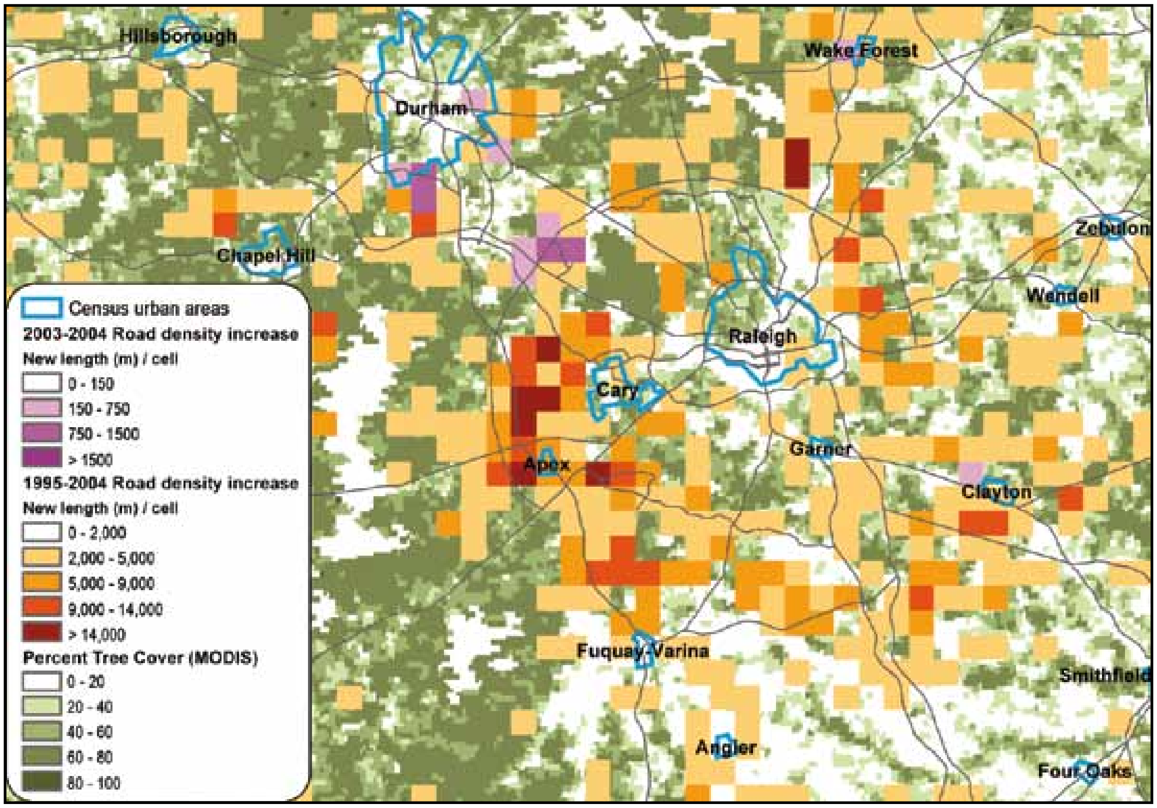

Figure 7—Use of road density change data to identify areas at risk for *Phytophthora ramorum* introduction. Changes in road density (total length of all road segments) for the Research Triangle region of North Carolina between 1995 and 2004 and between 2003 and 2004. Minimum resolution of individual cells is 4 km^2. Cells are color-coded according to the degree of change (cells with minimal change are omitted). This information is overlaid on a percentage tree cover map developed from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery.

context. We hope this will change, but we would also like to note some considerations for researchers who decide to perform similar investigations.

Utility of Above-Described Data Sets

There are basically three overriding issues with respect to these data sets: attribute resolution, spatial scale, and imperfect representation of the pathway-related variable of interest. Attribute resolution refers to the level at which a variable of interest is aggregated. As noted, commodity classifications in the foreign and domestic cargo data are usually quite broad, so it is difficult to track many specific commodities of interest (e.g., nursery plants). Rather, users must do one of two things. One way is to work with the tonnage values of the broader commodity category and assume that the spatial flow pattern of this broader category mirrors the pattern of the specific commodity of interest, so the relative ranking of different locations remains consistent. The alternative is to use ancillary data or some other means to estimate what percentage of the tonnage of the broader category belongs to the specific commodity of interest and how this percentage varies spatially across the area of analysis. The industry classification in the business location databases such as ReferenceUSA is, at times, similarly broad (e.g., we can identify nurseries, but not exactly which plants they grow or sell). This is a caveat that business location databases may be good for examining spatial patterns and trends, but should be used sparingly, if at all, for analyzing individual locations.

Related to the issue of attribute resolution is spatial scale, or the size of the geographic units at which the data are summarized. We have noted how the Commodity Flow Survey summarizes domestic commodity flow data at multiple scales, but the finest scale is at the level of metropolitan area. The Freight Analysis Framework databases are similarly scaled at the metropolitan area level. This is not necessarily problematic, although it should be considered when choosing a working scale for a risk map that incorporates multiple pathway data layers as well as climate and host distribution information. In cases where the resolution of attribute information is tied to the output spatial scale (e.g., the Commodity Flow Survey database), the user should evaluate whether more specific attribute information is worth the tradeoff in geographic specificity. Naturally, this may depend on the pest of interest.

Finally, many of the data sets are imperfect, surrogate representations of a particular risk of interest. This is especially true of the land use/landcover data. As an example, change in road density may generally suggest where there are areas of increased residential or commercial development, and this, in turn, may suggest where nursery plants infected with a pathogen or infested by an insect are likely to be planted. These may be reasonable assumptions for portraying the variability of relative risk across a landscape. However, it is important to consider the potential uncertainty that comes with using indirect measures.

Availability and Accessibility

Many of the data sets described here are free or can be purchased for a small fee. Most may be downloaded directly through the Internet, although some must be ordered on disk (e.g., the Commodity Flow Survey and the National Transportation Atlas Databases, both of which will be shipped to the requesting individual at the agency's expense). Some of the statistical data sets are already in database format (e.g., the FAF databases, which are in Microsoft Access), although most are comma-delimited data that may be assembled into a database by the user. In terms of data accessibility, there are two notable exceptions. First, the business location databases typically require a subscription (see "Business Location Databases"). Also, the roads data use to assess contemporary land use/landcover change are only available to ESRI ArcGIS software users with a license for the optional StreetMap extension.

The timespan of the available data varies widely owing to both when the data are collected, and how often their parent agencies analyze them and report the results. The current pattern suggests that many of the commodity flow data sets will be updated roughly every 5 years, although this likely depends on how much analysis time is required. For data sets that have previous versions, there have often been changes in how the data were processed or summarized between versions. We would advise potential users to carefully note these differences if combining multiple time steps of one of these data sets. More generally, it is important to consider differences in temporal scale, as well as spatial scale, if working with multiple data sources.

If initiating an analysis similar to what has been described in this synthesis, a few Internet sites offer a good place to start when searching for additional data sets:

- U.S. Army Corps of Engineers, Navigation Data Center: http://www.iwr.usace.army.mil/ndc/index.htm
- U.S. DOT Bureau of Transportation Statistics, TranStats Data Warehouse: http://www.transtats.bts.gov/
- University of Wisconsin-Madison, SILVIS Laboratory: http://www.silvis.forest.wisc.edu/
- U.S. Census Bureau, Business and Industry page: http://www.census.gov/econ/www/index.html
- U.S. Census Bureau, Geography page: http://www.census.gov/geo/www/index.html

Areas of Future Research

We will continue to search for additional data sets to represent human-mediated pathways in forest pest risk maps, but such a large data mining task would clearly benefit from the contributions of additional researchers and analysts. Some areas of significant data need include urban forest spatial distribution and condition, as well as recreational or informal pathways (e.g., movement of firewood) by which humans may spread forest pests. In addition, some of the data sets we have identified in our pest-focused research may be useful for examining other forest threats. For instance, we have only discussed insect and pathogen forest pests, but many of the same pathways are likely applicable for invasive plants. There are strong possibilities for researching the cross-applicability of these data sets.

A major challenge for forest pest risk mapping is the integration of multiple data sources with different attribute, spatial, and temporal scales in a single model for a given pest. This includes the combination of disparate data on host species, environmental factors, and pathways of spread. Basically, forest pest risk mapping has many of the same problems as other analyses that involve ranking or classification with large, complex data sets. First, it can be difficult to select the most significant variables out of a large suite of model inputs. Second, even if the most important variables can be selected, it is also difficult to define appropriate threshold values for ranking risk. It is our experience that these thresholds are often determined ad hoc or through expert opinion. Although this can be an adequate approach, additional research on quantitative techniques for building robust, parsimonious risk models would be fruitful (e.g., Downing and others, this volume). Moreover, there may be opportunities to combine quantitative risk assessment with quantitative analysis of different management options, revealing how they might affect the distribution of risk (Woodbury and Weinstein, this volume).

Spatial and thematic accuracy, the propagation of error, and the characterization of uncertainty in spatial data sets—as well as how these characteristics may influence the forest pest risk mapping process–are often downplayed in the need to quickly derive a useful risk map product for forest planners. The issues have really never been considered for the human-mediated pathways data described in this synthesis, which have only recently been adapted to a risk mapping context. Research opportunities abound in terms of developing quantitative techniques to address some of these issues in the forest pest risk-assessment process.

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