

Introduction

Biological invasions represent one of the most significant environmental threats to the maintenance of natural forest ecosystems in North America and elsewhere (Liebhold and others 1995), and have been estimated to cause more than \$100 billion annually in damage and control costs (Pimentel and others 2000). However, these costs do not take into account the economic value of nonmarket ecosystem services such as landscape aesthetics, outdoor recreation, and the knowledge that healthy forest ecosystems exist (Holmes and others 2009). Failure to address biotic invasions could result in severe consequences, including wholesale loss of natural resources in some regions, disruption of the natural processes that supply ecological services important to humans, and the impoverishment of ecosystems with the spread of cosmopolitan species (Mack and others 2000).

Plant invaders are a particular environmental concern because they can alter fire regime, nutrient cycling, hydrology, and energy budgets in native ecosystems, and can greatly diminish the abundance or survival of native species (Mack and others 2000). At least 138 non-indigenous tree and shrub species in the United States have invaded native forest and shrubland ecosystems (Pimentel and others 2000), with several of these species displacing native plant species and, in turn, reducing populations of some associated native animal species (Office of Technology Assessment 1993).

Because nonnative species continue to be introduced to the United States from other countries via trade and transportation, it is increasingly important to synthesize existing data on nonnative species abundance and distributions (Crall and others 2006). The Forest Inventory and Analysis (FIA) Program of the Forest Service, U.S. Department of Agriculture, offers a potentially important source of information about nonnative tree abundance and distributions because the data are collected from a large network of standardized forest plots across the conterminous United States, selected using a standardized sampling intensity (Reams and others 2005).

Analyses using these FIA data may help quantify the invasiveness of nonnative species, while also identifying locations in which nonnative tree species are concentrated and where they may have the most significant ecological impacts. Such information may aid in management decisions regarding the detection and control of nonnative tree species.

Methods

The primary objective of this work was to generate two sets of metrics, one quantifying the invasiveness of individual nonnative forest tree species, and the other measuring the prevalence of nonnative tree species, or “invadedness,” of each ecoregion section in the conterminous United States.

CRITERION 3—

Chapter 5. Large-Scale Assessment of Invasiveness and Potential Impact by Nonnative Tree Species

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To do this, we analyzed forest inventory data from 112,439 one-sixth-acre FIA plots. These plots represented the latest available FIA phase 2 tree [≥ 5 inch diameter at breast height (d.b.h.)] and sapling (≥ 1 inch d.b.h. and < 5 inches d.b.h.) inventory data as of February 2009 (FIA 2009). They encompassed the latest annualized data available or periodic data when a full cycle of annualized data was unavailable; most States in the last 10 years have moved to an annual inventory, in which each plot is re-measured on a regular basis (5-7 years in the East, 10 years in the West). The number of years required to complete earlier periodic surveys varied based on the availability of resources and the number of plots and field crews (McRoberts 2005). The FIA program inventories only forested land, which is defined as being at least 1 acre in extent and at least 10 percent stocked by forest trees of any size, or as formerly having such tree cover and not currently developed for a nonforest use (Reams and others 2005). As a result, nonnative forest trees invading grasslands are not recorded, until and unless the invasion results in the area qualifying as forest. Not all exotic tree species found on FIA plots have species codes in the FIA system, particularly those that are not commonly found and/or have recently been introduced to forests in the United States; the presence of these uncommon and recently introduced species was recorded instead using a generic hardwood or conifer species code. This may result in a slight underestimate of the overall presence of exotic species existing on FIA plots, so our measures of ecoregion “invadedness” by exotic species may in turn be slightly underestimated.

Two types of nonnative tree species were included in the study: (1) those with origins outside North America, referred to here as “exotic” species, and (2) those native to North America but occurring outside their historical distributions, referred to here as “non-indigenous native” species. Potentially non-indigenous native tree species included in the FIA database were identified within the Biota of North America county-level plant species distribution data (Kartesz 2009) as those with different portions of their ranges classified as “native” and “adventive or introduced/native.” Non-indigenous occurrences of these species were included in the study if at least 10 trees occurred on two or more FIA plots outside a 100-km buffer drawn around the historic range map of the species (U.S. Geological Survey 1999). Trees within these buffers, created using ArcGIS 9.2 (ESRI 2006), were excluded to ensure that our analyses did not include natural populations missed by the historic range maps as well as newer natural populations established since the creation of the maps in the mid-20th century. This buffer corresponds with the greatest distance trees are expected to be able to migrate without assistance over a 100-year timeframe, given that trees migrated a maximum of 100 km per year following the most recent glaciation (McLachlan and others 2005).

We report four metrics of “invasiveness” for each tree species included in the study: (1) overall abundance in the FIA data; (2) overall abundance of saplings [≥ 1 inch and < 5 inch diameter at breast height (d.b.h.)], as

a proxy for reproductive success; (3) number of ecoregion sections in which the species occurs, as a measure of geographic spread; and (4) mean percent of trees per acre represented by the species on the plots on which it occurs, as a measure of local ecological impact.

Additionally, we report four metrics of “invadedness” at the ecoregion section scale. Each of these metrics was reported separately for exotic nonnative species, for non-indigenous native species, and for all nonnative species, a category which encompasses all the species included in the other two classifications. The four metrics of “invadedness” are (1) number of nonnative tree species at the ecoregion scale, as a measure of nonnative species richness; (2) percent of plots within each ecoregion section containing at least one nonnative tree or sapling, as a measure of nonnative distribution across the ecoregion; (3) the mean percent of nonnative species basal area, across plots within each ecoregion, as a measure of local ecological impact; and (4) the mean percent of nonnative saplings per acre, across plots within each ecoregion, as an indicator of nonnative species reproductive success.

Results and Discussion

Of the nearly 3.1 million individual trees recorded in the FIA data and used in our analyses, 21,338, or 0.69 percent, were classified as nonnative. Of the 21,338 nonnative trees, 12,944 were exotic nonnatives (60.66 percent) and 8,394 were non-indigenous natives (39.34 percent).

In our results, the most abundant tree, a non-indigenous native, was Osage-orange (*Maclura pomifera*) (table 5.1), which was widely prevalent in the FIA data throughout the Midwestern States, outside of its native range of eastern Texas, southeastern Oklahoma, and southwestern Arkansas. Before barbed wire had become available, Osage-orange had been planted across large areas of the United States and southeastern Canada as a living fence, because the species reproduces well in full sun from the large seed crops it produces in most years (Preston and Braham 2002).

In our results, Scots pine (*Pinus sylvestris*) was the most abundant exotic nonnative species, relatively common throughout the Great Lakes States and the Northeast. With a large distribution across the northern reaches of Eurasia, this species has been widely used in reforestation for pulpwood, erosion control, and Christmas tree plantations in the parts of the Northern United States where it has become locally naturalized (Hardin and others 2001).

The third most abundant tree in our results also had the most saplings, suggesting recent introduction and/or reproduction. Despite its abundance, Chinese tallow-tree (*Triadica sebifera*) thus far exists in only 15 ecoregion sections in the Southeast, many fewer than other abundant nonnatives (table 5.1). Exhibiting very rapid growth, this species is a major pest of coastal tallgrass prairies and a persistent invader of abandoned agricultural lands and bottomland hardwoods of the Southeast (Hardin and others

2001). It invades stream banks, riverbanks, and wet areas like ditches as well as upland sites, and it is spread by bird- and water-dispersed seeds in addition to colonizing by prolific surface root sprouts (Miller 2003).

Among species with relatively high abundance, the Australian exotic *Melaleuca quinquenervia* appears to have the most significant ecological impact, encompassing an average of 54.88 percent of the trees per acre on the plots where it occurs (table 5.1). This prolific and rapidly growing species is of considerable environmental concern in southern Florida, where it was planted to lower water tables, to stabilize shore lines, and to create windbreaks (Liebhold and others 1995). Other abundant exotic species with apparently high local ecological impacts (i.e., occurring on more than 25 FIA plots) are Chinese tallow-tree, Russian-olive (*Elaeagnus angustifolia*), tungoil tree (*Vernicia fordii*), and Siberian elm (*Ulmus pumila*).

The species richness of nonnative tree species is much higher in the Eastern half of the country than in the West, where they are largely absent (fig. 5.1). Of the 106 ecoregions containing at least one nonnative species, all but three are in the East, and only a handful of ecoregions in the East lack nonnatives. The sections containing the most nonnative species are generally in the interior portions of the East, with the South Central Great Lakes region (222J) having the most (19), followed by the Southern Unglaci-

Table 5.1—Four metrics of “invasiveness” for nonnative tree species: overall abundance in the Forest Inventory and Analysis data, overall abundance of saplings, number of ecoregion sections in which each species occurs, and the mean percent of trees per acre represented by each species on the plots on which it occurs

Species	Trees	Saplings	Sections	Mean relative tpa
<i>Maclura pomifera</i> ^a	3,558	463	37	23.61
<i>Pinus sylvestris</i>	3,243	267	41	26.80
<i>Triadica sebifera</i>	3,156	1,364	15	31.23
<i>Robinia pseudoacacia</i> ^a	2,095	306	55	23.39
<i>Picea abies</i>	1,891	90	33	23.53
<i>Ailanthus altissima</i>	1,822	592	34	18.64
<i>Pinus taeda</i> ^a	779	52	14	26.97
<i>Melia azedarach</i>	640	198	24	18.06
<i>Picea glauca</i> ^a	442	33	16	24.32
<i>Ulmus pumila</i>	412	61	33	27.13
<i>Melaleuca quinquenervia</i>	325	158	6	54.88
<i>Morus alba</i>	325	90	35	13.43
<i>Pinus strobus</i> ^a	260	21	13	22.30
<i>Carya illinoensis</i> ^a	240	49	14	15.23
<i>Picea pungens</i> ^a	237	47	12	27.14
<i>Paulownia tomentosa</i>	220	46	20	8.63
<i>Pinus nigra</i>	213	3	14	21.58
<i>Albizia julibrissin</i>	188	85	28	15.89
<i>Pinus virginiana</i> ^a	185	36	17	6.72
<i>Prunus avium</i>	142	13	15	7.44
<i>Pseudotsuga menziesii</i> ^a	138	9	9	29.50
<i>Catalpa speciosa</i> ^a	118	13	17	15.77
<i>Elaeagnus angustifolia</i>	107	86	10	37.92
<i>Gleditsia triacanthos</i> ^a	81	17	18	13.18
<i>Acer platanoides</i>	77	24	14	22.55
<i>Quercus palustris</i> ^a	52	7	13	8.30
<i>Catalpa bignoniodes</i> ^a	42	9	11	10.63

continued

Table 5.1—Four metrics of “invasiveness” for nonnative tree species: overall abundance in the Forest Inventory and Analysis data, overall abundance of saplings, number of ecoregion sections in which each species occurs, and the mean percent of trees per acre represented by each species on the plots on which it occurs (continued)

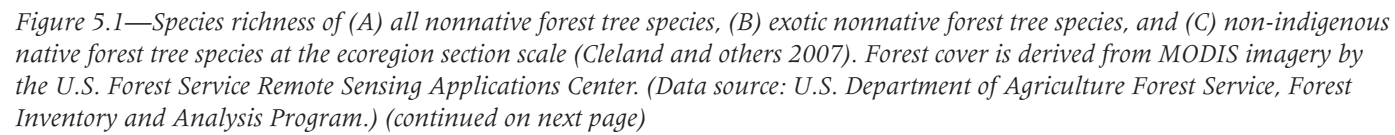
Species	Trees	Saplings	Sections	Mean relative tpa
<i>Alnus glutinosa</i>	36	3	9	14.64
<i>Vernicia fordii</i>	32	21	3	28.02
<i>Catalpa</i> spp. ^a	31	1	8	13.46
<i>Quercus michauxii</i> ^a	31	4	8	7.13
<i>Carya laciniosa</i> ^a	29	10	10	9.60
<i>Cinnamomum camphora</i>	20	9	4	23.61
<i>Salix alba</i>	20	3	10	10.59
<i>Magnolia grandiflora</i> ^a	19	9	4	11.80
<i>Pinus banksiana</i> ^a	18	3	4	36.55
<i>Eucalyptus grandis</i>	17	6	1	100.00
<i>Magnolia acuminata</i> ^a	15	8	4	11.96
<i>Castanea dentata</i> ^a	14	8	2	55.14
<i>Eucalyptus</i> spp.	11	0	1	46.89
<i>Pinus ponderosa</i> ^a	10	0	3	5.81
<i>Populus nigra</i>	7	3	2	77.21
<i>Citrus</i> spp.	7	7	2	41.26
<i>Salix sepulcralis</i>	7	0	4	16.22
<i>Castanea mollissima</i>	6	0	4	12.15
<i>Populus alba</i>	5	2	1	47.82
<i>Casuarina lepidophloia</i>	4	0	1	63.64
<i>Eucalyptus globulus</i>	3	1	3	18.34
<i>Sorbus aucuparia</i>	3	3	2	11.16
<i>Tamarix</i> spp.	2	2	1	100.00
<i>Syzygium cumini</i>	2	0	1	10.00
<i>Prunus persica</i>	1	0	1	0.70

^a Species are “non-indigenous native” tree species that are native to North America, but occurring outside their historic ranges.

Allegheny Plateau (221E) with 18, and by the Coastal Plains-Middle (231B) and the Northern Ridge and Valley (M221A), each having 16 (fig. 5.1A). Patterns of abundance of exotic nonnatives (fig. 5.1B) and non-indigenous natives (fig. 5.1C) were generally similar.

Ecoregion sections with the greatest distribution of nonnative species (having the highest percentage of FIA plots containing a nonnative species) tended to encompass a relatively small amount of forest cover and to be located in the central part of the country (fig. 5.2A). In the sparsely forested South Central and Red Bed Plains (332F), for example, 61.9 percent of forest plots included a nonnative species. More than 40 percent of plots in three other sections also included at least one nonnative tree: the Western Glaciated Plains (332B), the Louisiana Coastal Prairie and Marshes (232E), and the Osage Plains (251E). Exotic nonnatives tended to be more common in ecoregion sections along the Gulf Coast, in the Mid-Atlantic States, and in the eastern portions of the Midwest (fig. 5.2B), while non-indigenous native trees were more prevalent in the central Midwest and in the Southern Plains States (fig. 5.2C).

Nonnative trees had the greatest apparent ecological impact along the Gulf Coast and on the Great Plains, where these species constituted the highest mean percentage of basal area at the plot level (fig. 5.3A). The ecoregions with



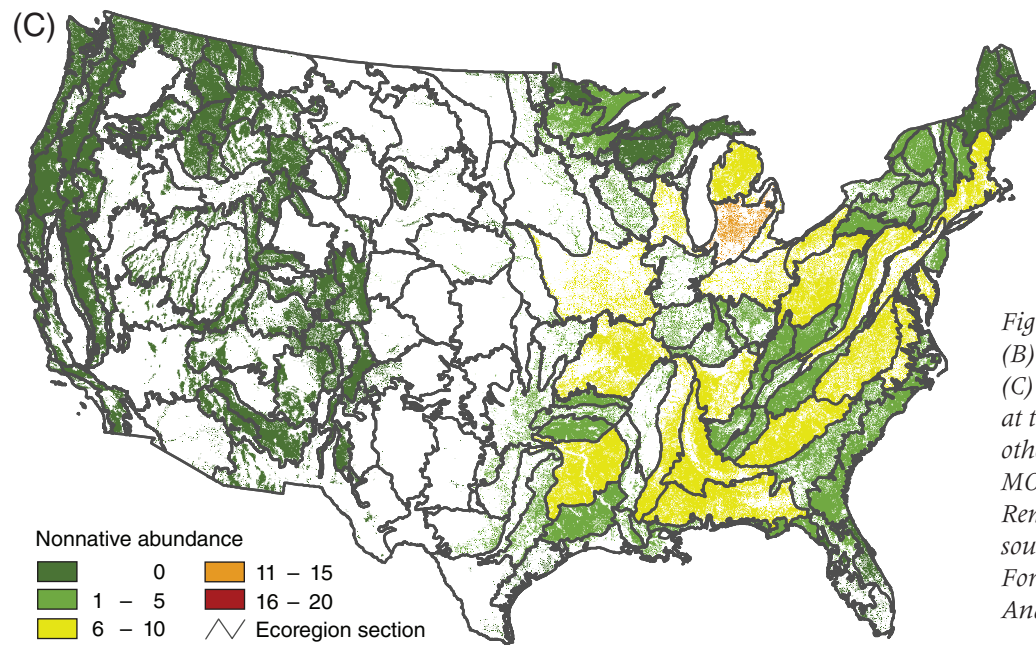
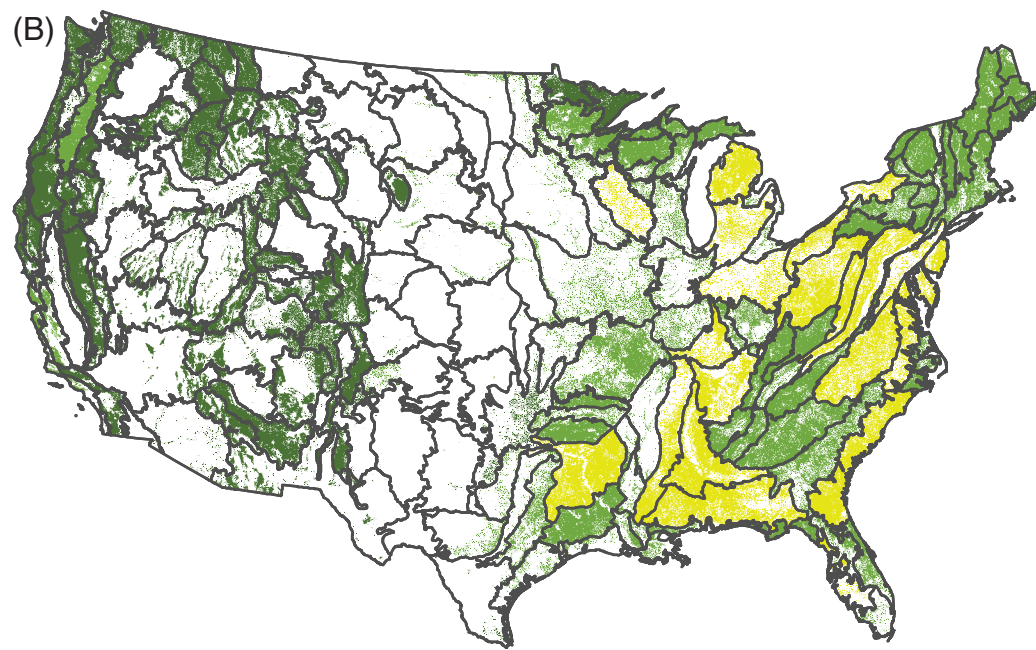


Figure 5.1 (continued)—Species richness of (B) exotic nonnative forest tree species, and (C) non-indigenous native forest tree species at the ecoregion section scale (Cleland and others 2007). Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.)

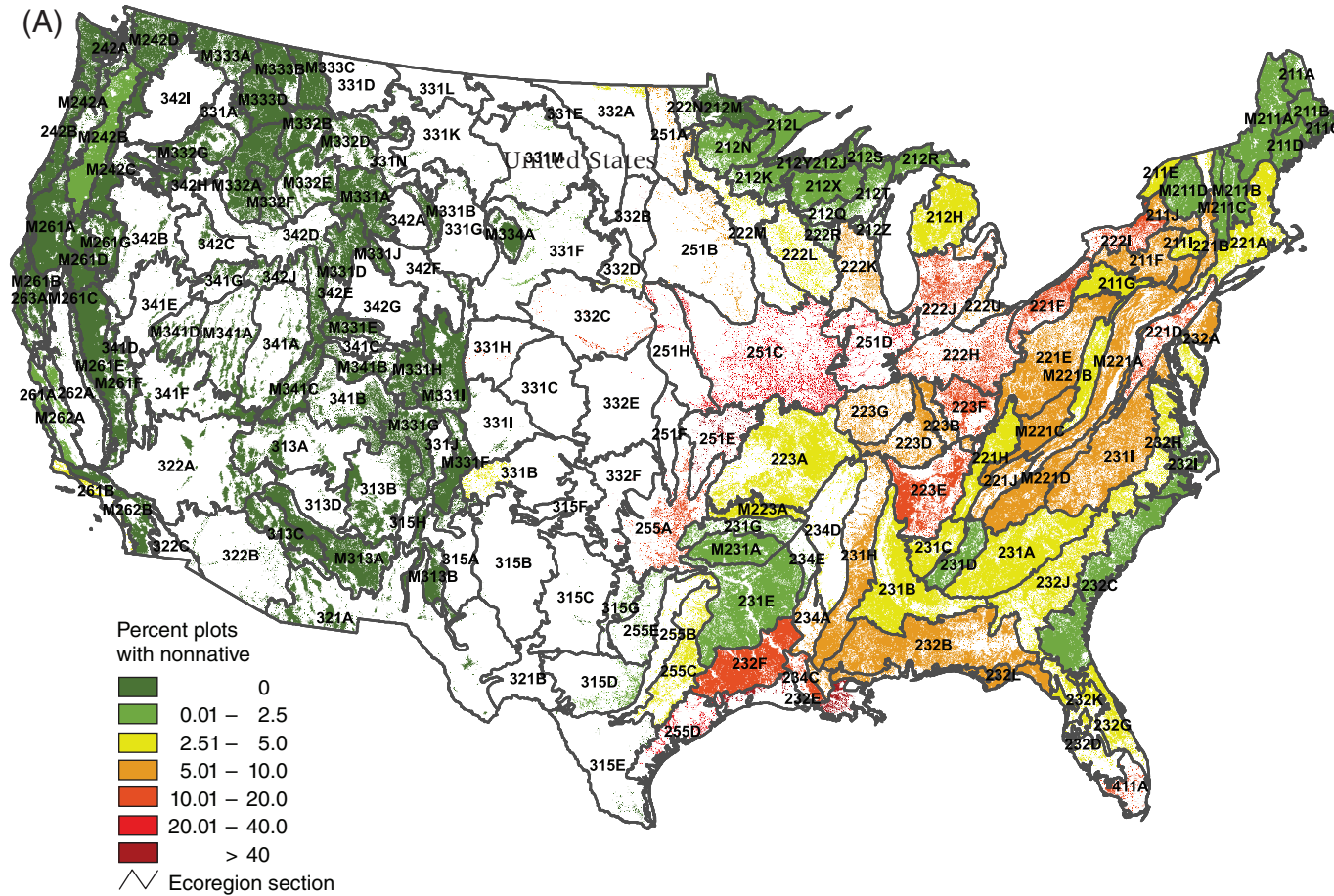


Figure 5.2—Percent of Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007) containing at least one (A) nonnative tree, (B) exotic nonnative tree, and (C) non-indigenous native tree. Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.) (continued on next page)

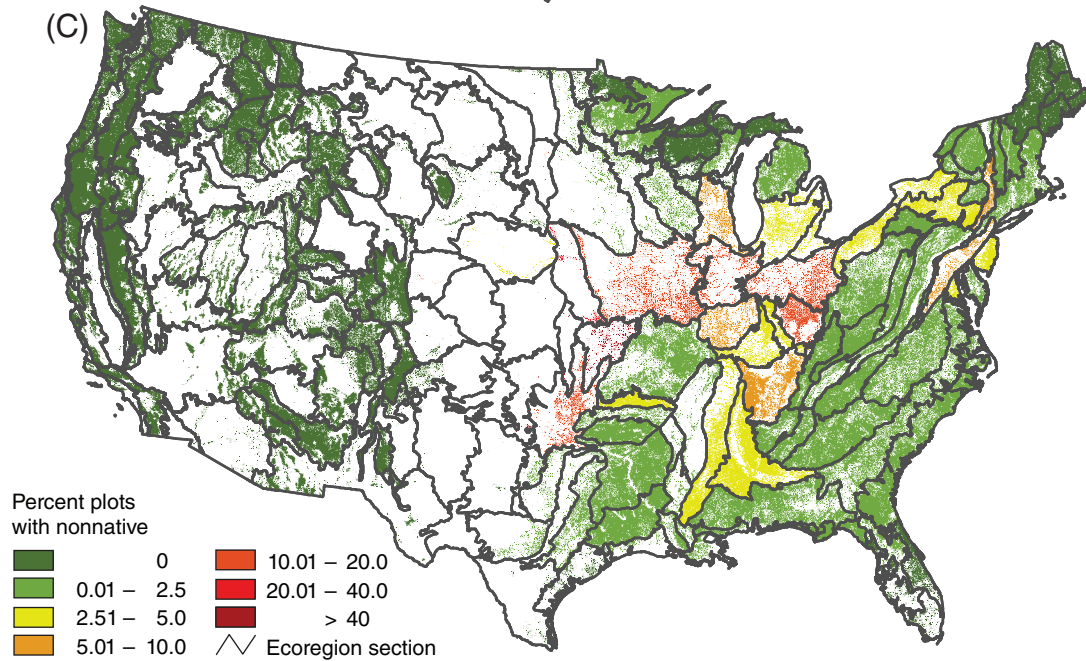
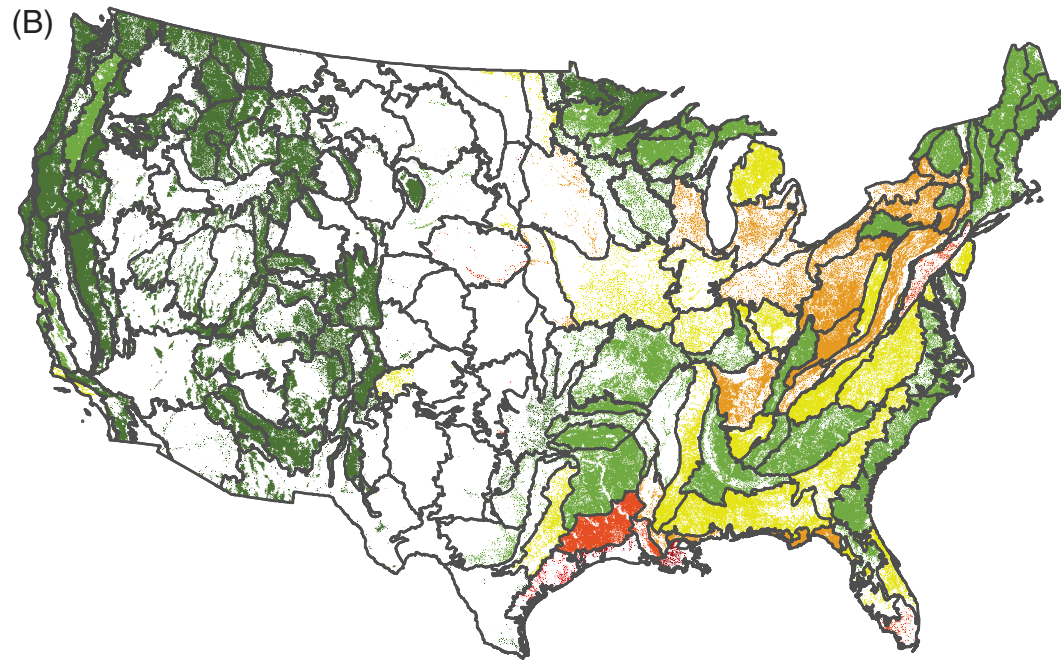


Figure 5.2 (continued)—Percent of Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007) containing at least one (B) exotic nonnative tree, and (C) non-indigenous native tree. Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.)

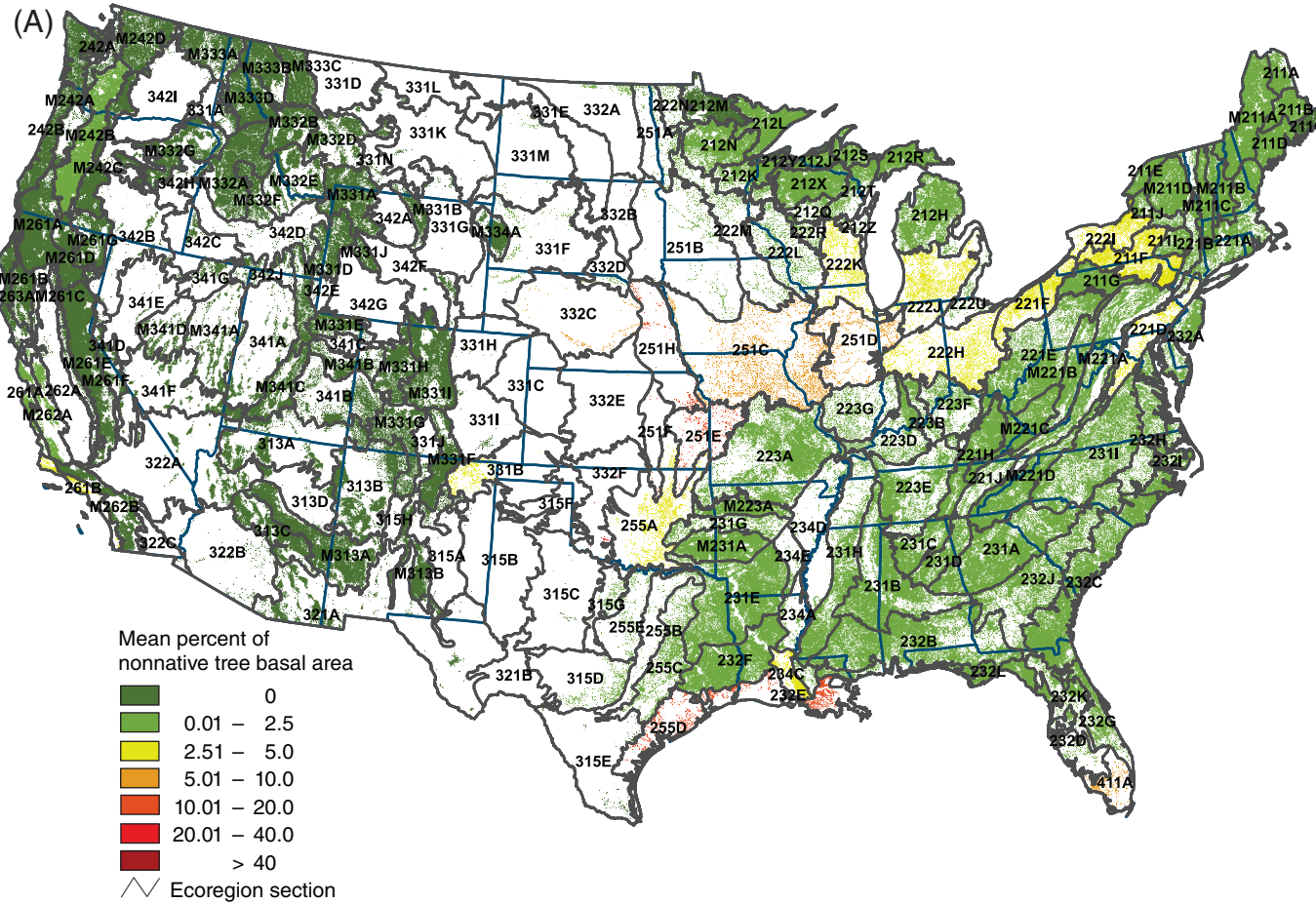
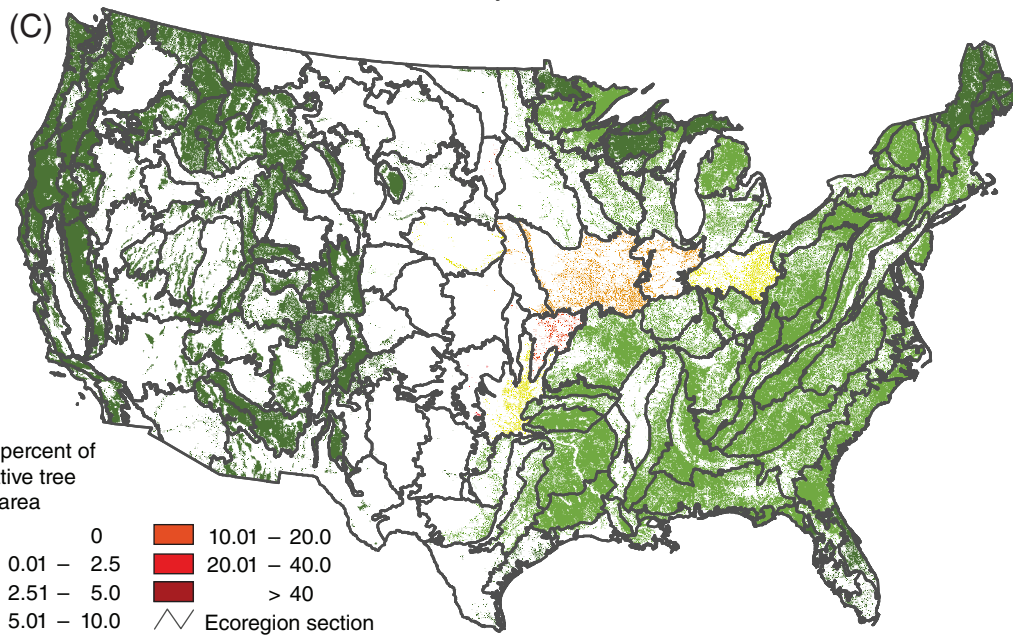
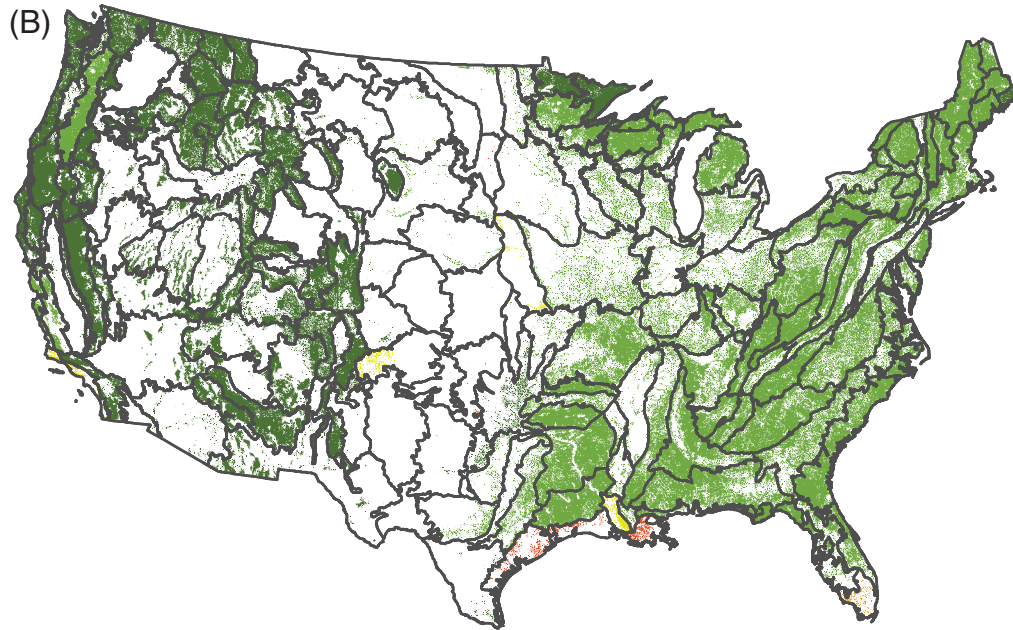


Figure 5.3—Mean percent of plot-level basal area that is (A) nonnative, (B) exotic nonnative, and (C) non-indigenous native, across Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007). Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.) (continued on next page)



the highest percent of nonnative basal area contain very little forest cover: just under half of the basal area in the Western Glaciated Plains (332B), for example, was not native (47.9 percent), compared to 34.7 percent in the South Central and Red Bed Plains (332F), and 15.1 percent in the Flint Hills (251F). Among more heavily forested areas, meanwhile, the Louisiana Coastal Prairie and Marshes (232E) and the Central Gulf Prairie and Marshes (225D) had the highest percentage of nonnative basal area, with 15.0 percent and 10.9 percent, respectively. Exotic trees appear to have had a greater potential impact along the Gulf Coast and in southern Florida (fig. 5.3B) while non-indigenous native trees may have had a greater potential impact in the Midwest (fig. 5.3C).

Patterns of nonnative sapling occurrence at the plot level (fig. 5.4) appear to differ in some significant ways from the analysis of nonnative basal area across all tree sizes. Sections with large percentages of plots containing a nonnative sapling are concentrated along the Gulf Coast, on the Great Plains, and in southern California

Figure 5.3 (continued)—Mean percent of plot-level basal area that is (B) exotic nonnative, and (C) non-indigenous native, across Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007). Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.)

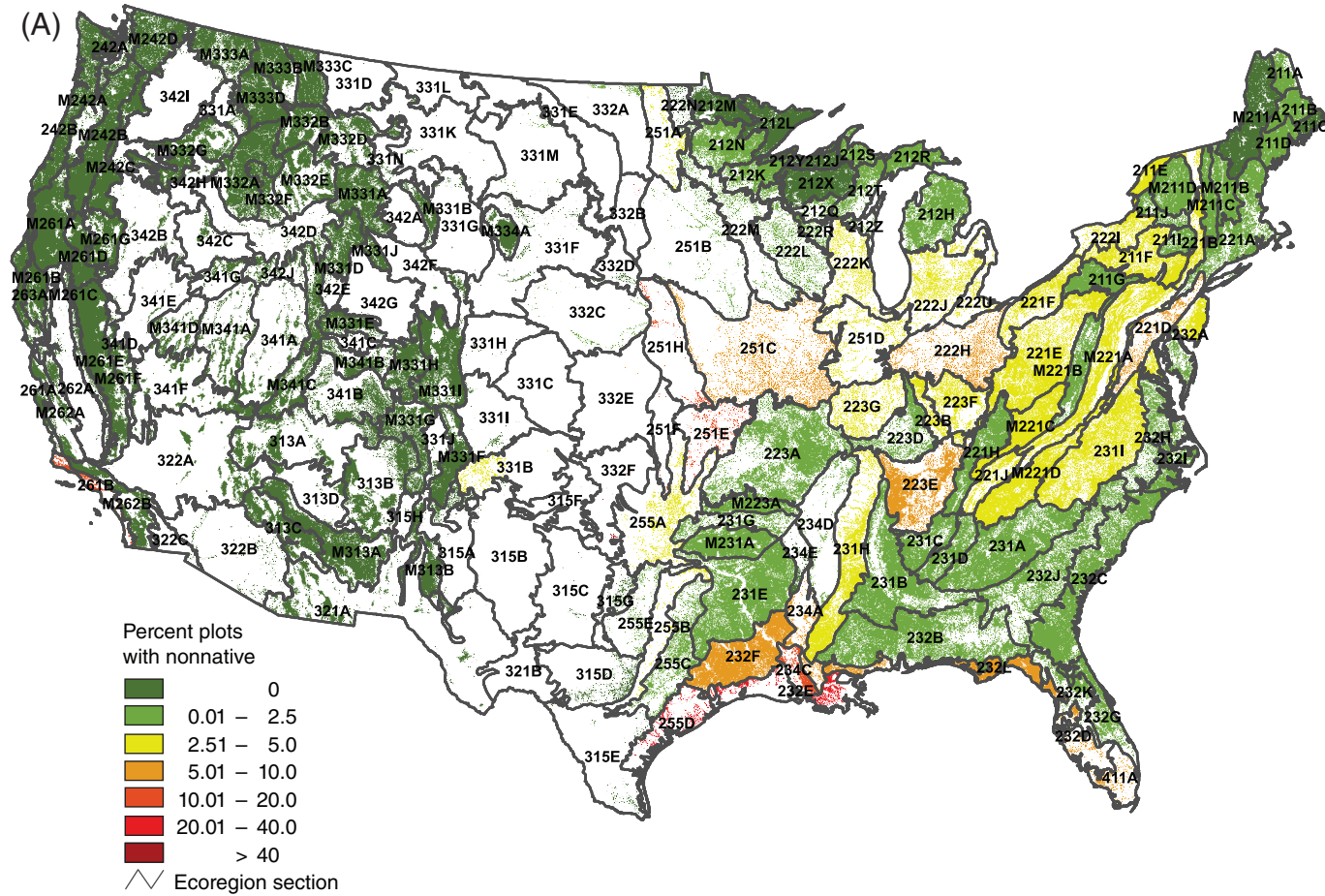
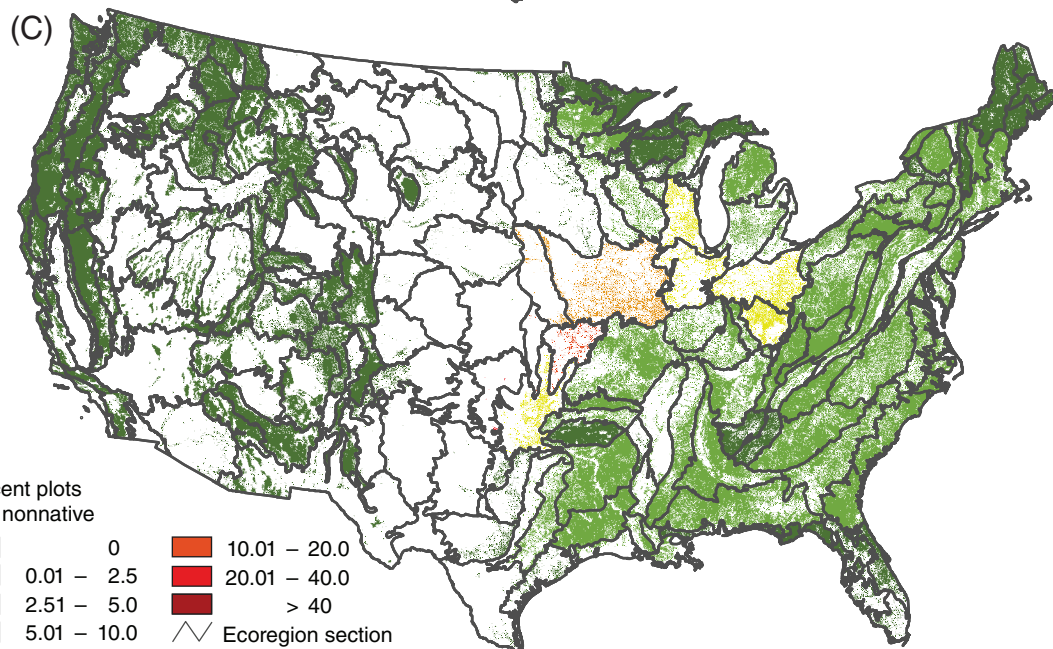
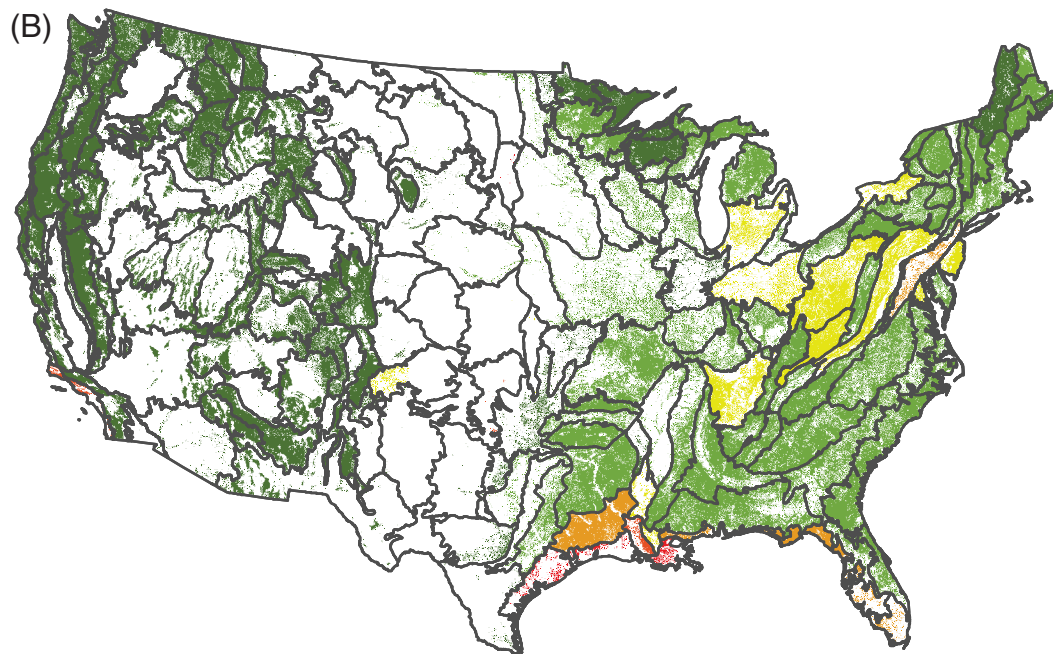


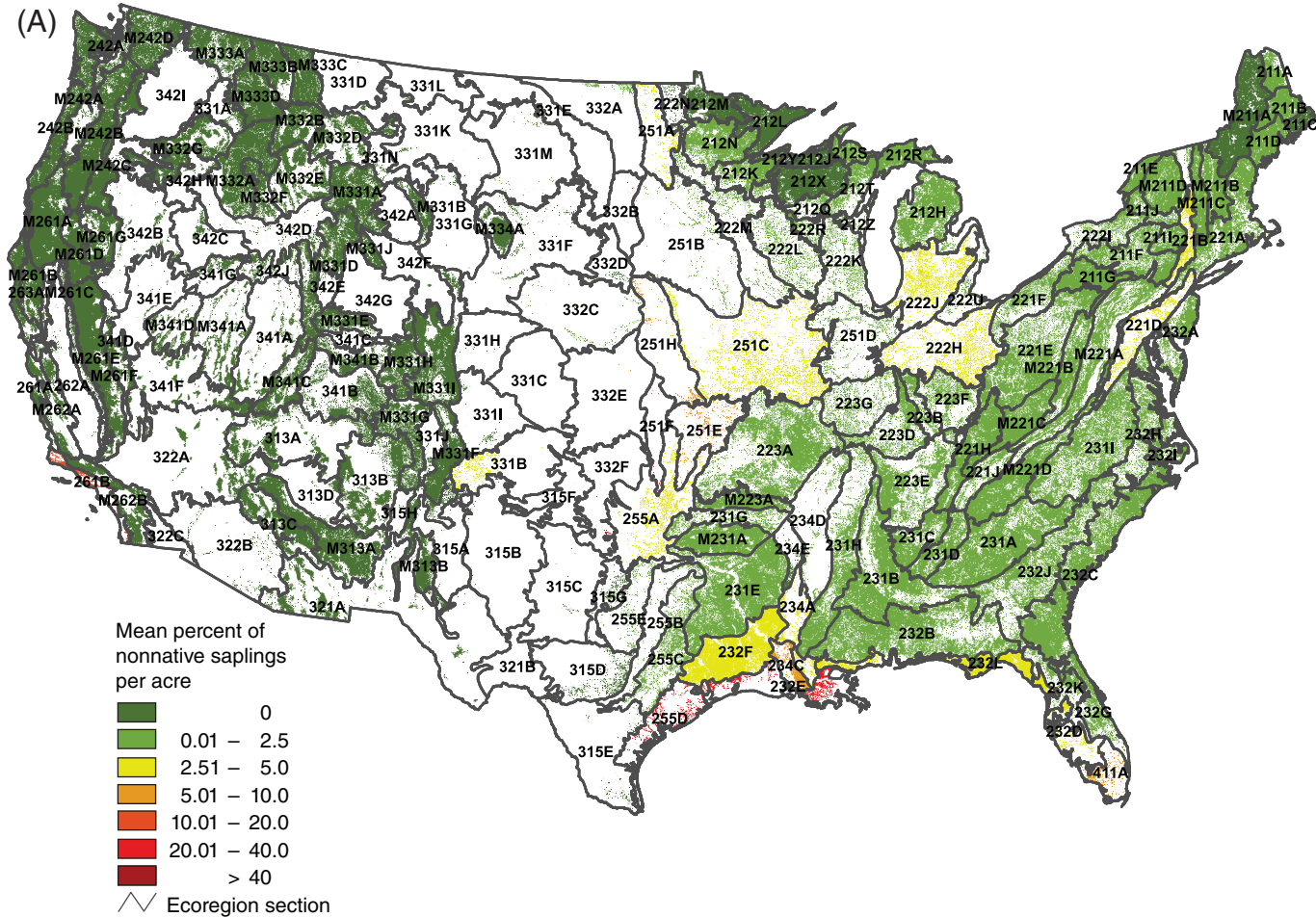
Figure 5.4—Percent of Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007) containing at least one (A) nonnative sapling, (B) exotic nonnative sapling, and (C) non-indigenous native sapling. Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.) (continued on next page)



(fig. 5.4A). The widespread distribution of exotic saplings is limited almost entirely to the Gulf Coast, southern Florida, and southern California (fig. 5.4B), while the widespread distribution of non-indigenous native saplings is confined to the Midwest (fig. 5.4C). These findings are largely consistent with the analysis of the ecological impact of nonnative saplings, as measured by the mean percentage of trees per acre at the plot level that are not native. It appears that the relative importance of all nonnative saplings is highest along the western Gulf Coast, southern California, and in southern Florida (fig. 5.5A), places where exotic nonnative saplings seem most important (fig. 5.5B). Non-indigenous native saplings are most important in a handful of sections in the southern Great Plains region (fig. 5.5C).

This work was designed to offer insights into the invasiveness of specific forest tree species and into the extent to which those species may impact ecological processes across large ecological regions. Such information may be useful to assist in the targeting of activities to

Figure 5.4 (continued)—Percent of Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007) containing at least one (B) exotic nonnative sapling, and (C) non-indigenous native sapling. Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.)



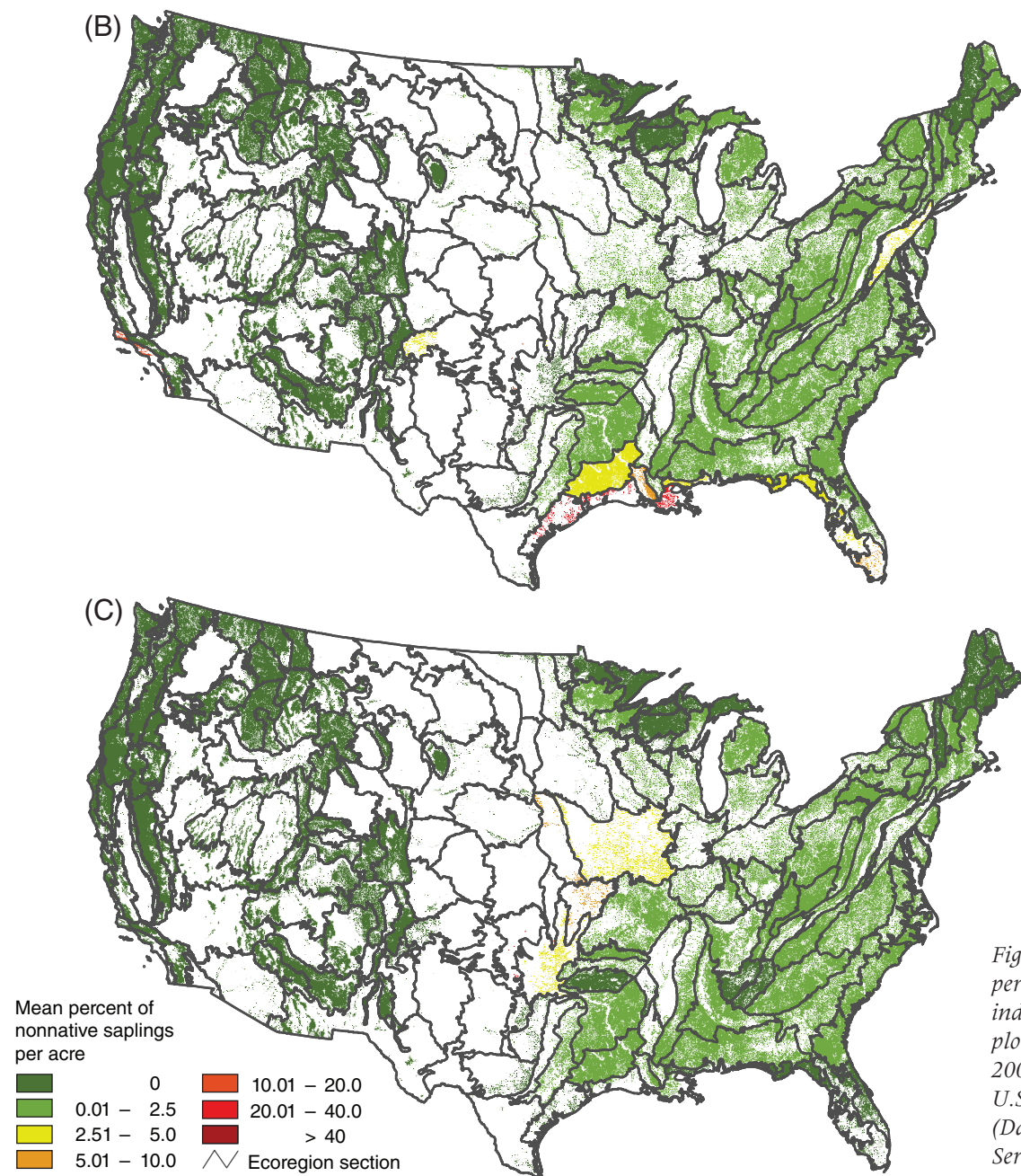


Figure 5.5 (continued)—Mean percent of total saplings per acre that are (B) exotic nonnative, and (C) non-indigenous native, across Forest Inventory and Analysis plots at the ecoregion section scale (Cleland and others 2007). Forest cover is derived from MODIS imagery by the U.S. Forest Service Remote Sensing Applications Center. (Data source: U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program.)

detect and suppress nonnative tree species. As data become available, we recommend repeating these analyses for other plant habits, such as herbaceous plants and shrubs, which often tend toward greater invasiveness than forest tree species.

Literature Cited

- Cleland, D.T.; Freeouf, J.A.; Keys, J.E. [and others]. 2007. Ecological subregions: sections and subsections for the conterminous United States. Sloan, A.M., tech. ed. Gen. Tech. Report WO-76. Washington, DC: U.S. Department of Agriculture Forest Service. Map, presentation scale 1:3,500,000; Albers equal area projection; colored. Also as a GIS coverage in ArcINFO format on CD-ROM or at http://fsgeodata.fs.fed.us/other_resources/ecosubregions.html. [Date accessed: March 18, 2011].
- Crall, A.W.; Meyerson, L.A.; Stohlgren, T.J. [and others]. 2006. Show me the numbers: what data currently exist for nonnative species in the USA? *Frontiers in Ecology and the Environment*. 4(8): 414–418.
- ESRI. 2006. ArcMap 9.2. Redlands, CA: Environmental Systems Research Institute Inc.
- Forest Inventory and Analysis (FIA). 2009. The forest inventory and analysis database: database description and users manual version 3.0 for phase 2. Arlington, VA: United States Department of Agriculture Forest Service. 243 p.
- Hardin, J.W.; Leopold, D.J.; White, F.M. 2001. Harlow and Harrar's textbook of dendrology, ninth edition. Boston: McGraw Hill. 543 p.
- Holmes, T.P.; Aukema, J.E.; Von Holle, B. [and others]. 2009. Economic impacts of invasive species in forests past, present, and future. In: Ostfeld, R.S.; Schlesinger, W.H., ed. *Year in ecology and conservation biology 2009*. Oxford: Blackwell Publishing: 18–38.
- Kartesz, J.T. 2009. A synonymized checklist and atlas with biological attributes for the vascular flora of the United States, Canada, and Greenland. version 2.0 [CD-ROM]. Chapel Hill, NC: Biota of North America Program, North Carolina Botanical Garden, University of North Carolina.
- Liebholt, A.M.; MacDonald, W.L.; Bergdahl, D.; Mastro, V.C. 1995. Invasion by exotic forest pests: a threat to forest ecosystems. *Forest Science Monographs*. 41(2): 1–49.
- Mack, R.N.; Simberloff, D.; Lonsdale, W.M. [and others]. 2000. Biotic invasions: Causes, epidemiology, global consequences, and control. *Ecological Applications*. 10(3): 689–710.
- McLachlan, J.S.; Clark, J.S.; Manos, P.S. 2005. Molecular indicators of tree migration capacity under rapid climate change. *Ecology*. 86(8): 2088–2098.
- McRoberts, R.E. 2005. The enhanced Forest Inventory and Analysis program. In: Bechtold, W.A.; Patterson, P. L., ed. *The enhanced Forest Inventory and Analysis program—national sampling design and estimation procedures*. Asheville, NC: United States Department of Agriculture Forest Service, Southern Research Station: 1–10.
- Miller, J.H. 2003. Nonnative invasive plants of southern forests: a field guide for identification and control. Revised. Gen. Tech. Rep. SRS-62. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 93 p.
- Office of Technology Assessment. 1993. Harmful non-indigenous species in the United States. Washington, DC: United States Congress, Office of Technology and Assessment. 391 p.
- Pimentel, D.; Lach, L.; Zuniga, R.; Morrison, D. 2000. Environmental and economic costs of non-indigenous species in the United States. *Bioscience*. 50(1): 53–65.
- Preston, R.J.; Braham, R.R. 2002. *North American Trees*, Fifth Edition. Ames, IA: Iowa State University Press. 514 p.
- Reams, G.A.; Smith, W.D.; Hansen, M.H. [and others]. 2005. The Forest Inventory and Analysis sampling frame. In: Bechtold, W.A.; Patterson, P.L., ed. *The enhanced Forest Inventory and Analysis program—national sampling design and estimation procedures*. Asheville, NC: United States Department of Agriculture Forest Service, Southern Research Station: 11–26.
- U.S. Geological Survey. 1999. Digital representation of “Atlas of United States Trees” by Elbert L. Little, Jr. <http://esp.cr.usgs.gov/data/atlas/little/>. [Date accessed: March 13, 2009].