What Does "Local" Firewood Buy You? Managing the Risk of Invasive Species Introduction

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ABSTRACT Firewood can serve as a vector in the transport of non-native species, including wood-boring insects that feed within the wood and thus can be transported accidentally. Governments have enacted limitations on the movement of firewood in an effort to limit the anthropogenic movement of non-native species through, for example, recreational camping. Although the movement of invasive species through firewood is a documented invasion pathway, it is not trivial for governments to determine a "safe" allowable distance for moving firewood. We were motivated by this challenge and developed a theoretical simulation to determine the campgrounds that could be potentially exposed to infested firewood based upon the hypothetical distribution of an invasive species and the allowable distance for moving firewood. We extend this concept to the known distributions of emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) and Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) Coleoptera: Cerambycidae). We illustrate, based upon theoretical and empirical observations, that as the distribution of an invasive species increases, more rigid constraints on the movement of firewood would be required relative to those species that are distributed over a smaller scale. Also, on the level of management within a state, smaller states have far less margin for error than larger ones, as even extremely rigid restrictions on the movement of firewood could have little management effect unless the infested area is spatially limited. These results collectively suggest the potential for a dynamic management strategy that adjusts allowable distances for firewood movement based upon the distribution of the non-native species.

KEY WORDS Asian longhorned beetle, biological invasions, emerald ash borer, firewood, invasive species management

The movement of non-native species within and between continents has accelerated in recent years due to increases in trade and travel (Perrings et al. 2005, McCullough et al. 2006, Hulme et al. 2008). Non-native species can pose a significant threat to the composition and functioning of ecosystems and can be accidentally transported to new habitats through a variety of vectors such as infested plants (Reichard and White 2001, Work et al. 2005), solid wood packaging materials (Brockerhoff et al. 2006, Gu et al. 2006), ballast water (Ruiz et al. 2000, Drake and Lodge 2004), and personal airline luggage (Liebhold et al. 2006). One transport vector that has received considerable attention is firewood in which wood boring immature insects could be transported accidentally (GAO 2006, Muirhead et al. 2006). No more is this evident than in the case of the emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), which has the potential to effectively extirpate native North American ash (*Fraxinus* spp.) (Poland and McCullough 2006). Another wood-boring invasive insect affecting North American forests that can be potentially transported in firewood is the Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae) (Nowak et al. 2001).

The emerald ash borer, native to Asia, was first discovered in the Detroit area of Michigan in 2002 (Poland and McCullough 2006), although dendrochronological studies have suggested that it first became established in North America at least by 1996–1997 (Siegert et al. 2007). It has now been reported in 13 states and two provinces in the United States and Canada. Adult females oviposit eggs in the crevices of the bark, and upon hatching larvae tunnel into the tree and feed on the cambium and phloem. Development can take up to 2 yr, and adults emerge through D-shaped emergence holes. All species of North American *Fraxinus* are known to be susceptible to attack, and extensive larval feeding kills the host tree.

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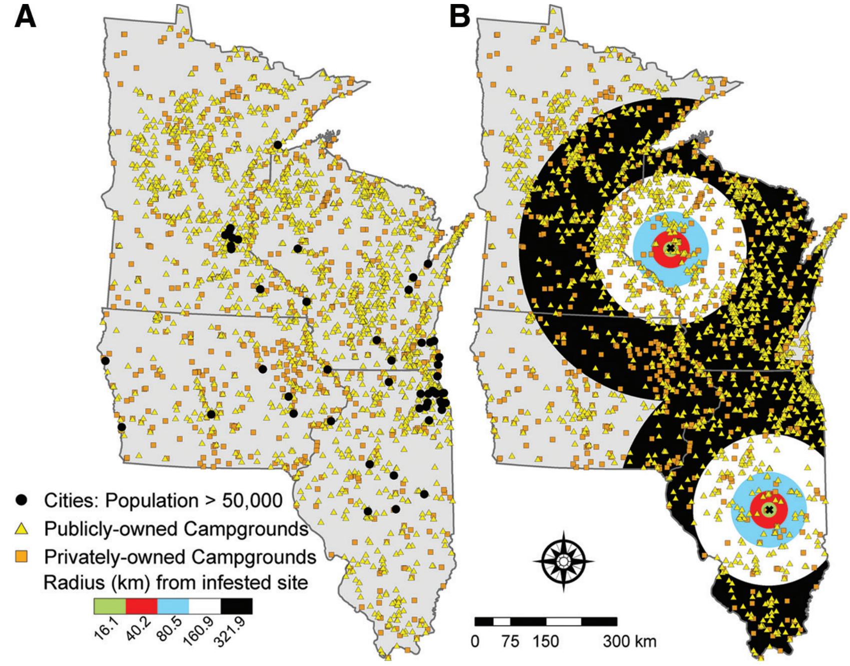

Fig. 1. (A) Spatial distribution of publicly and privately owned campgrounds within region 1, and cites with a population ≥50,000. (B) Example iteration of the regionwide model. Two infested sites (crosses) were randomly selected, from which campgrounds that were within a 16.1-, 40.2-, 80.5-, 160.9-, or 321.9-km radius of the infested sites were counted. This was replicated 500 times and when using different numbers of infested sites.

The Asian longhorn beetle, native to China and Korea, was initially discovered infesting trees in the United States in 1996 (Nowak et al. 2001), and localized infestations have since been reported in the urban forests of Chicago, IL; New York and Long Island, NY; Jersey City, NJ; and Toronto, ON, Canada. In 2008, a large infestation was detected in Worcester, MA, and the full extent of the infestation is now known to exceed 19,000 ha (Baca et al. 2009). Female beetles deposit one egg in an oviposition niche under the bark. Upon hatching, early instars feed between the inner bark and sapwood for up to a month. Late instars tunnel into the heartwood and feed for up to 2 yr, pupate, and then emerge as adults through round holes that they bore (Keena 2006). Like *A. planipennis,* trees are generally killed after attack by *A. glabripennis.* The beetles attack a number of deciduous host trees, including maple (*Acer* spp.), elm (*Ulmus* spp.), and willow (*Salix* spp.).

Because of the importance of firewood as a potential vector for the anthropogenic movement of these and other non-native wood boring insects, as well as the potential for firewood to be transported over long distances for recreational use, state and federal governments have enacted limitations on its movement to limit the accidental introduction of invasive species (e.g., NY Environmental Conservation Law Section 9-1303, Part 192.5; Wisconsin Administrative Code, Chapter ATCP 21.17; U.S. Code of Federal Regulations, 7CFR 301.53-1 through 9). However, it can be challenging for governments to determine an allowable distance for moving firewood, such as for recreational camping use, and regulations could vary from state-to-state (EAB Information 2010). We were motivated by this challenge and explored the conceptual situation of anthropogenic movement of firewood for recreational campground use by quantifying the number of campgrounds at varying distances from a hypothetical range of a non-native species. We also extend this theoretical approach to the known distributions of *A. planipennis* and *A. glabripennis,* in the midwestern and New England-New York regions of the United States, respectively.

Materials and Methods

Campground Data. Spatial locations of campgrounds were compiled from several sources and divided into subsets by ownership: publicly owned (e.g., county, state, and federally managed campgrounds) and privately owned. A complete list of sources is presented in *Appendix* 1. We considered two regions in our analysis: region 1, the midwestern states of Iowa, Illinois, Minnesota, and Wisconsin; and region 2, the New England states of Massachusetts, Connecticut, Rhode Island, Vermont, New Hampshire, Maine, and New York. There were 313 and 1,553, and 333 and 1,047 publicly and privately owned campgrounds, respectively, within regions 1 and 2, respectively. We considered these two regions because they each provided a complementary

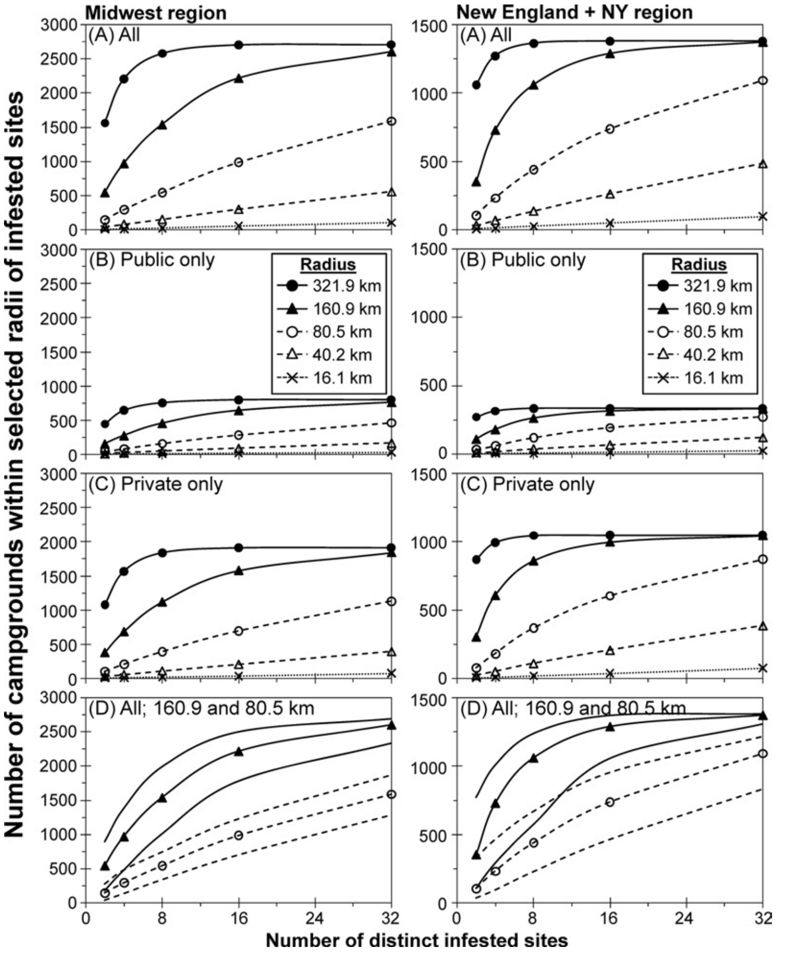

Fig. 2. Mean number of all (A), publicly owned (B), and privately owned (C) campgrounds within each radius relative to the number of infested sites for regions 1 and 2. (D) For each region, the mean and 95% confidence intervals are shown for the 80.5- (dashed lines) and 160.9 (solid lines)-km radii.

empirical example: *A. planipennis* in region 1 and *A. glabripennis* in region 2.

Regional Analysis. We first considered all states in each region as one area. We developed a simulation model using ESRI ArcObjects (Redlands, CA) to randomly select 2, 4, 8, 16, or 32 spatially discrete point locations, or "infested sites," within the region. The number of campgrounds that were within a 16.1-, 40.2-, 80.5-, 160.9-, and 321.9-km (10-, 25-, 50-, 100-, and 200-mile, respectively) radius of each infested site was determined. We used a bootstrap method (500 replications) to estimate the mean and 95% confidence intervals (by using the 2.5 and 97.5 percentiles of the bootstrapped distribution; Efron and Tibshirani 1993) of the number of campgrounds by the number of infested sites that fell within the specified radius of infested sites. We considered both ownerships (public and private) combined and then separated. An example of one iteration based upon two infested sites is shown in Fig. 1.

Regional Analysis: City Introduction Only. We also modified the above simulation model so that infested sites could only be selected from cities within each region with a human population ≥50,000 (Fig. 1). We did this because many initial detections of a new non-native species tend to occur in areas with higher human populations, which is probably due to stronger invasion pathways into cities (such as through trade routes) as well as the increased probability that someone will notice the damage caused by a new, non-native species (i.e., dead or dying trees in an urban landscape and the subsequent potential liability of hazardous trees). In this case, we combined public and privately owned campgrounds.

State-by-State Analysis. We also used the same model to determine—for each state—the number of campgrounds (private and public combined) that fell within 16.1, 40.2, 80.5, 160.9, or 321.9 km of infested sites. In this case, we only selected infested sites within the state, and only considered campgrounds within the state. Considering each state separately also allowed us to consider the relationship among allowable radius, the number of infested

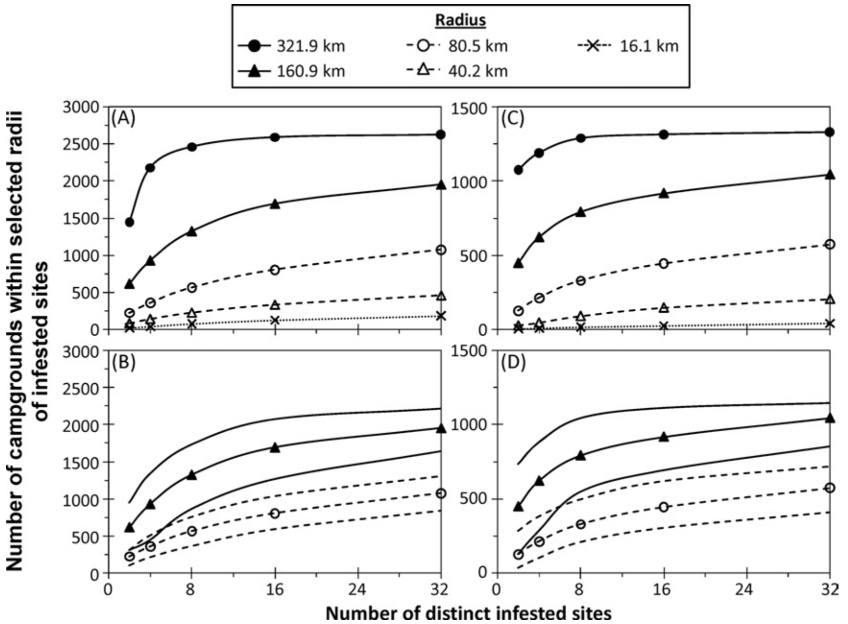

Fig. 3. City introduction only: mean number of all campgrounds within each radius relative to the number of infested sites for regions 1 (A) and 2 (C) when allowing only cities >50,000 in population to be selected as infested sites. The mean and 95% confidence intervals are shown for the 80.5- (dashed lines) and 160.9 (solid lines)-km radii for regions 1 (B) and 2 (D).

sites, and the area of the state. In this case, we quantified the mean proportion of each state's campgrounds (based upon the bootstrapped distribution with 500 replications) relative to the total area of each state, which ranged from 4,002 (Rhode Island) to 225,171 km^2 (Minnesota), that fell within a set radius (16.1, 40.2, 80.5, 160.9, or 321.9 km) given the number of infested sites (2, 4, 8, 16, or 32). Data were fit using locally weighted polynomial regression in R (R Development Core Team 2009).

Empirical Examples: *A. planipennis* and *A. glabripennis*. We used the above conceptual approaches with the known distributions of *A. planipennis* in region 1, and *A. glabripennis* from region 2, both as of December 2009 as codified under the U.S. Code of Federal Regulations, Subtitle B, Chapter III, Parts 301.51-3 and 301.53-3. In each region, we counted the number of publicly or privately owned campgrounds that fell within 16.1, 40.2, 80.5, 160.9, or 321.9 km of the distribution for each species.

Results and Discussion

The mean number of all campgrounds, publicly owned campgrounds only, and privately owned campgrounds only that fell within a set radius from a range of initial infested sites was similar between regions 1 and 2 (Fig. 2). The highest radii (160.9 and 321.9 km) seemed to be most sensitive to the number of infested locations, and nonlinearly increased more dramatically as the number of infested sites increased relative to the other radii. When contrasting the bootstrapped mean and associated 95% confidence intervals between the 160.9- and 80.5-km radii (Fig. 2D), there were overlapping confidence intervals when the number of infested sites was ≤4 in region 1, and ≤9 in region 2. We observed similar results in both regions when we considered only cities ≥50,000 in population as initial infested sites (Fig. 3).

When considering each state separately, similar patterns between the number of infested sites and the proportion of each state's campgrounds that fell within a set radius were observed, although the size of the state, as expected, was particularly important (Fig. 4). Even when the number of infested sites is 2, an allowable radius as small as 40.2 km in a small state still resulted in a mean proportion >0.8 of the state's campgrounds to be within this allowable radius. Moreover, when the number of infested sites ≥8, an allowable radius of 16.1 km in a small state would still allow >65% of the state's campgrounds to be within this radius. Regardless of state size, as the number of infested sites increased to eight or more, at least half of a state's campgrounds were within a radius of 80.5 km or more (Fig. 4).

The consequence of increasing the allowable radius for moving firewood for recreational purposes is also apparent when using the known distributions of *A. planipennis* in region 1, and *A. glabripennis* in region 2 (Fig. 5). Both species are considered to be established at multiple, spatially disjunct sites, some of which can include a considerable area, such as *A. planipennis* in Wisconsin and *A. glabripennis* in Massachusetts. The number of campgrounds that are within a set radius increases nonlinearly with in-

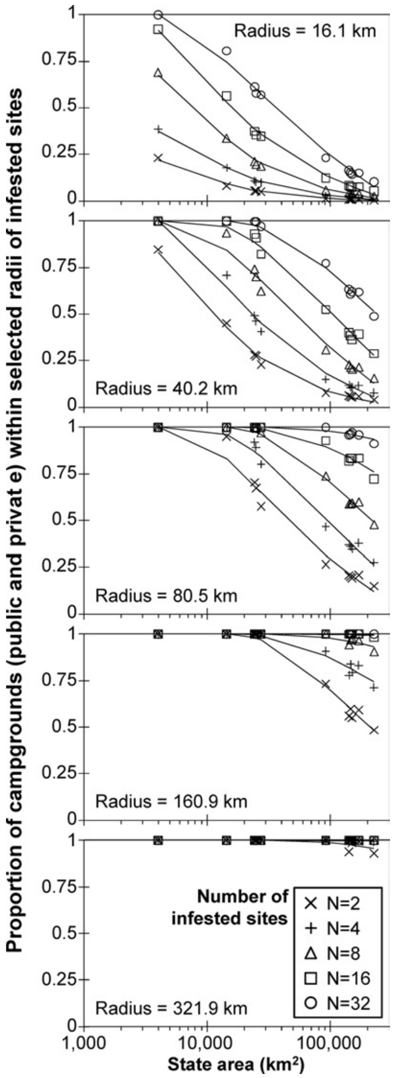

Fig. 4. Relationship between state area (both regions combined) and proportion of each state's campgrounds that is within an increasing radius (top to bottom) given an initial number of infested sites (symbols).

creasing radius. For example, the number of campgrounds that fall within 16.1, 40.2, and 80.5 km of the known distribution of *A. planipennis* increases from 172 to 276 to 484, respectively, whereas for *A. glabripennis,* the number of campgrounds increases from 41 to 72 to 193, respectively (Fig. 5). At an allowable distance of 160.9 km, 170 publicly owned and 399 privately owned campgrounds would fall within the 2009 known distribution of *A. planipennis,* whereas 76 publicly owned and 303 privately owned campgrounds would fall within the 2009 known distribution of *A. glabripennis.* Although a campground that falls within an allowable radius for moving firewood does not always equate to the introduction and subsequent establishment of *A. planipennis, A. glabripennis,* or any other non-native species transported in or on firewood, these results do highlight the regulatory challenges of managing firewood movement as a potential vector for the introduction of unwanted species.

These results also collectively suggest a possible dynamic strategy for managing this potential invasion pathway, particularly so for larger states. For example, more rigid constraints on the movement of firewood, which are probably more costly to implement than less rigid constraints, could be imposed at a time when the area is thought to be composed of multiple infested areas (Figs. 2 and 3). Although we are not proposing more relaxed standards in efforts to regulate the movement of firewood, these results do highlight a potential for a more dynamic approach to regulation, which could be more cost-effective. Smaller states have a much lower margin for error, as even extremely rigid restrictions on the movement of firewood, such as within a 16.1-km radius, could have little management effect unless the state had very few infested sites (Fig. 4). For species that become spatially widespread, such as *A. planipennis,* which in addition to the states we used in our analysis is also established throughout the lower peninsula of Michigan (U.S. Code of Federal Regulations, Subtitle B, Chapter III, Part 301.53-3), restrictions on the movement of firewood for recreational purposes may not be sufficient unless a very rigid restriction is enforced. It is also important to note that the majority of campgrounds in these regions are privately owned, which could be far more difficult to regulate than publicly owned campgrounds.

The anthropogenic movement of non-native species into new areas continues to be an increasing threat to ecosystem function and biodiversity (Mack et al. 2000, Pimentel et al. 2005, Lockwood et al. 2007). Because our analyses only considered the movement of firewood for recreational camping due to its importance as a potential vector for the anthropogenic movement of non-native species, future work could focus on the use of wood as a fuel source for home heating, as well as other wood related products. Regulating vectors such as firewood can be extremely challenging, due to both the sheer volume of recreational campers that frequent campgrounds each year and public opposition to increasing regulations. Moreover, even when invasion pathways are well documented, there can be challenges for governments to legally regulate the movement of non-native species, as exemplified by the recent U.S. Supreme Court decision that refused, for the second time, to hear a motion from the states of Wisconsin, Minnesota, Ohio, Pennsylvania, Michigan, and New York (Nos. 2201org, 2202org, 2203org, U.S. Supreme Court) that sought to limit the introduction of Asian carp into Lake Michigan.

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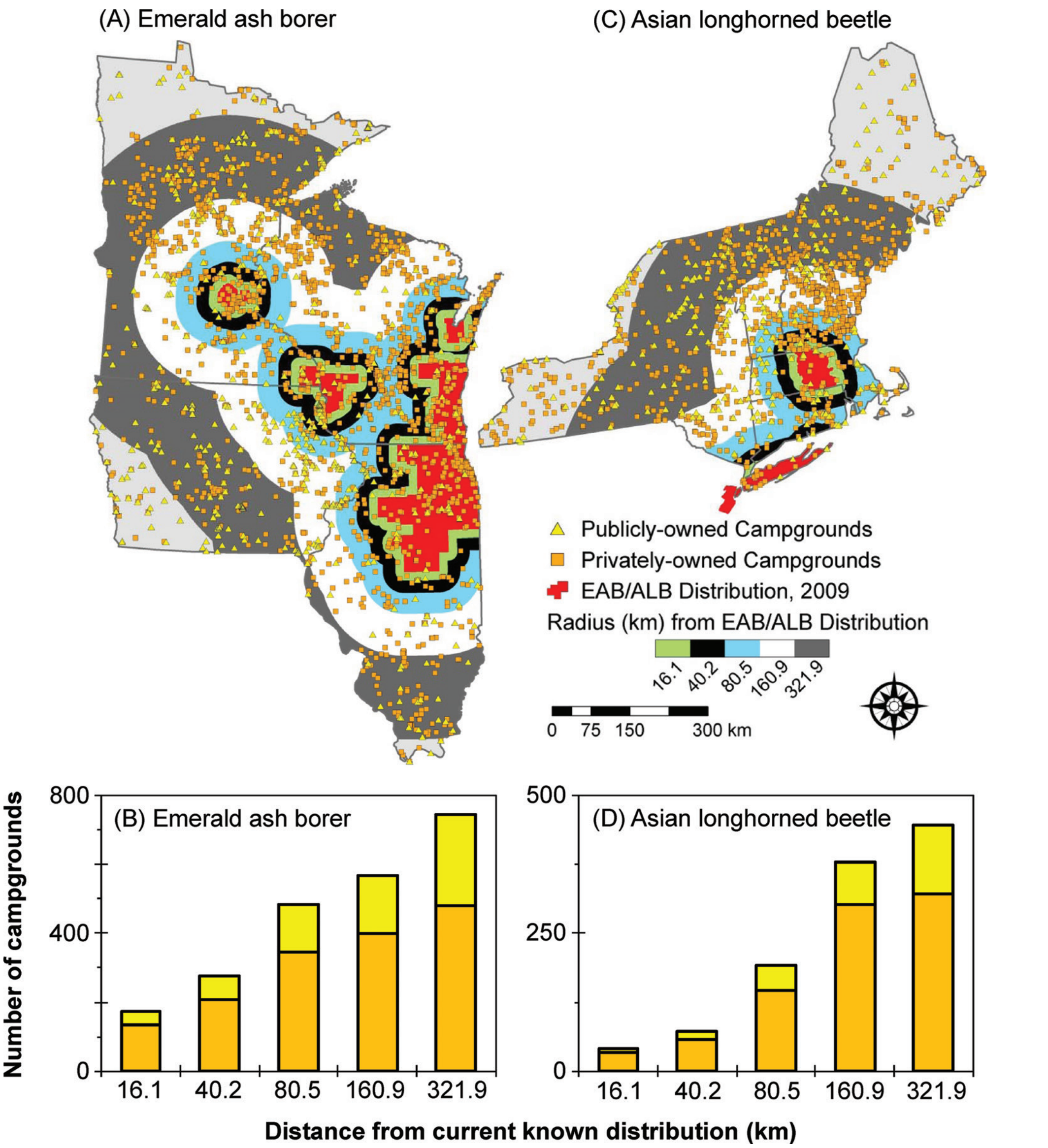

Fig. 5. The 2009 distribution of emerald ash borer (A) and Asian longhorned beetle (C), and the campgrounds that fall within different radii from their respective distributions, which are summarized in B and D as a function of ownership (orange, privately owned; yellow, publicly owned).

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Appendix 1. List of data sources used to compile a spatial dataset on publicly owned and privately owned campgrounds

State	Source	Data type	URL	Ownership
All	InfoUSA (2009)	Database	http://www.infousa.com/Home/home/190000	Private and public
Connecticut	Department of Environmental Protection (CT DEP)	Website directory	http://www.ct.gov/dep/cwp/view.asp?a=2716&q=325038&depNav_GID=1621&depNav=	State
Connecticut	U.S. Army Corps of Engineers (US ACE)–West Thompson Lake	Website	http://www.nae.usace.army.mil/recreati/wtl/wtlhome.htm	Federal
Connecticut	University of Connecticut Map and Geographic Information Center (MAGIC), Connecticut Office of Policy and Management (CT OPM), and Department of Environmental Protection (CT DEP)	GIS shapefile	http://magic.lib.uconn.edu/	State
Illinois	Department of Natural Resources (IL DNR)	Google Earth overlay, website directory	http://dnr.state.il.us/lands/Landmgt/Programs/Camping/index.htm	State
Iowa	Department of Natural Resources (IA DNR)	Website directory	https://eservices.iowa.gov/iowaparks/index.php?pgname=browsestateparks	State
Iowa	US ACE–Lake Red Rock	Website directory	http://www.mvr.usace.army.mil/RedRock/default.htm	Federal
Iowa	Natural Resources Geographic Information Systems (NRGIS) Library	GIS shapefile	http://www.igsb.uiowa.edu/nrgislibx/	
Iowa	Iowa Association of County Conservation Boards	Website directory	http://www.iaccb.com/index.php?option=com_content&task=view&id=25&Itemid=37	County
Iowa	mycountyparks.com	Website directory	http://mycountyparks.com	County
Maine	Department of Conservation (ME DOC)	Website directory	http://www.maine.gov/doc/parks/reservations/maps.html	State
Maine	National Park Service (NPS)–Acadia National Park	Website	http://www.nps.gov/acad	Federal
Maine	Maine GIS Data Catalog (MEGIS)	GIS shapefile	http://megis.maine.gov/catalog/	
Massachusetts	Department of Conservation and Recreation (Mass DCR)	Website directory	http://www.mass.gov/dcr/recreate/camping2.htm	State
Massachusetts	Massachusetts Geographic Information System (Mass GIS)	GIS shapefile	http://www.mass.gov/mgis/osp.htm	
Minnesota	Explore Minnesota	Database	http://www.exploreminnesota.com/camping	Private
Minnesota	Department of Natural Resources (MN DNR)	Website directory	http://www.dnr.state.mn.us/camping/index.html	State
Minnesota	Minnesota Department of Natural Resources GIS Data Deli (DNR Data Deli)	GIS shapefile	http://deli.dnr.state.mn.us/	State
Minnesota, Wisconsin	S. Hobrla. 1998. Public and Private Campgrounds of the Northern Lake States. USDA FS	Database	http://www.ncrs.fs.fed.us/gla/social/images/camp.gif	Private, County, State
New Hampshire	Divison of Parks and Recreation (NH DPR)	Website directory	http://www.nhparks.state.nh.us/state-parks	State
New Hampshire	New Hampshire Geographically Referenced Analysis and Information Transfer System (NH GRANIT)	GIS shapefile	http://www.granit.unh.edu/data/downloadfreedata/category/databycategory.html	State
New York	USDA FS–White Mountain National Forest	Website	http://www.fs.fed.us/r9/forests/white_mountain/recreation/camping/	Federal
New York	Department of Environmental Conservation (NYS DEC)	Website directory	http://www.dec.ny.gov/outdoor/7825.html	State
New York	Office of Parks, Recreation & Historic Preservation (NYS OPRHP)	Website directory	http://nysparks.state.ny.us/parks/park-results.aspx?a=754&ao=0&src=3	State
New York	USDA FS–Finger Lakes National Forest	Website	http://www.fs.fed.us/r9/forests/greenmountain/htm/fingerlakes/f_home.htm	Federal
New York	New York State GIS Clearninghouse	GIS shapefile	http://www.nysgis.state.ny.us/gisdata/	State
Reference map	ESRI–StreetMap USA Layer	GIS shapefile	Used as a reference to help locate campgrounds	State
Reference map	Google Maps	Map	http://maps.google.com/	State
Reference map	Recreation.gov	Map	http://www.recreation.gov/browseMapsRecGov.do?topTabIndex=CampgroundMap	Federal
Rhode Island	Rhode Island Department of Environmental Management (RI DEM)	Website directory	http://www.riparks.com/Camping%20in%20RIState%20Parks.htm	State
Rhode Island	Rhode Island Geographic Information System (RIGIS)	GIS shapefile	http://www.edc.uri.edu/rigis/data/data.aspx?ISO=environment	State
Vermont	Vermont Center for Geographic Information (VCGI) Recreational Sites Layer	GIS shapefile	http://www.vcgi.org/dataware/	State
Vermont	Vermont State Parks, Department of Forests, Parks and Recreation	Website directory	http://www.vtstateparks.com/	State
Wisconsin	Department of Natural Resources (WI DNR)	GIS shapefile	WI DNR Division of Forestry Layer from Courtney Klaus (courtney.klaus@wisconsin.gov)	State
Wisconsin	Department of Natural Resources (WI DNR)	Website directory	http://dnr.wi.gov/org/land/parks/reservation/campingparks.html	State