Incidence of Bark- and Wood-Boring Insects in Firewood: A Survey at Michigan's Mackinac Bridge

ROBERT A. HAACK,[1,2] TOBY R. PETRICE,[1] AND ALEX C. WIEDENHOEFT[3]

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ABSTRACT Firewood is a major pathway for the inadvertent movement of bark- and wood-infesting insects. After discovery of *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae) in southeastern Michigan in 2002, quarantines were enacted including prohibition of transporting firewood across the Mackinac Bridge between Michigan's Lower and Upper peninsulas. Drivers are required to surrender firewood before crossing the bridge. We surveyed recently surrendered firewood in April, July, and September 2008 and categorized it by genus, cross-sectional shape (whole, half, or quarter), approximate age (years since it was a live tree), presence of bark, and evidence of bark- and wood-boring insects. The 1,045 pieces of firewood examined represented 21 tree genera: primarily *Acer* (30%), *Quercus* (18%), *Fraxinus* (15%), *Ulmus* (12%), *Betula* (5%), and *Prunus* (5%). Live borers (Bostrichoidea, Brentidae, Buprestidae, Cerambycidae, Cossidae, Curculionidae [Scolytinae and non-Scolytinae], and Siricidae) were found in 23% of the pieces and another 41% had evidence of previous borer infestation. Of the 152 *Fraxinus* firewood pieces, 13% had evidence of past *A. planipennis* infestation, but we found no live *A. planipennis*. We discuss national "don't move firewood" campaigns and U.S. imports of fuelwood. During 1996–2009, the United States imported fuelwood valued at >$US98 million from 34 countries.

KEY WORDS exotic, firewood, fuelwood, invasive, pathway

There is a long tradition in the United States of people transporting firewood to camping, fishing, and hunting sites, as well to their primary and vacation homes (Reid and Marion 2005, Barzen et al. 2009, Peterson and Nelson 2009, Robertson and Andow 2009). However, there has been generally little public recognition of the threat posed by firewood as a pathway for movement of native and exotic (non-native) forest pests, such as insects and disease organisms. In recent decades, many exotic bark- and wood-boring insects were discovered in the United States (Haack 2006, Haack et al. 2009), and firewood was implicated as a likely pathway by which people have inadvertently moved some of these exotics to new areas after their initial introduction (Haack et al. 1997, McCullough et al. 2004, Cameron et al. 2008, MFC 2009, Robertson and Andow 2009).

The close relationship between borers and firewood is not surprising. There are thousands of bark- and wood-boring insect species in the United States and worldwide (Haack and Slansky 1987), with most belonging to the orders Coleoptera (e.g., Anobiidae, Bostrichidae [now including Lyctidae], Buprestidae, Cerambycidae, and Curculionidae [now including Platypodidae and Scolytidae]), Hymenoptera (e.g., Siricidae), and Lepidoptera (e.g., Cossidae and Sesiidae). Most borers infest trees that are stressed, dying, or recently dead (Haack and Slansky 1987, Hanks 1999, Lieutier et al. 2004), and firewood is commonly cut from trees in these same conditions.

The most nutritious portion of a live tree trunk or branch is the cambial region that is found at the interface between the inner bark and wood. In general, the inner bark transports photosynthates from the crown downward, whereas the outer sapwood transports water and minerals from the soil upward (Pallardy 2007). As a result, borers tend to colonize first the cambial region followed by the sapwood and heartwood. This pattern of succession in the bark- and wood-infesting insects has been documented since the late 1800s (Townsend 1886, Blackman and Stage 1924, Graham 1925, Savely 1939, Gardiner 1957, Fager 1968). In addition, borer voltinism patterns reflect the nutritional differences among the various woody tissues. For example, considering species in temperate climates, borers that develop mostly in the cambial region tend to complete one or more generations per year. By contrast, borers that develop mostly in sapwood usually require 1–2 yr, whereas those that develop mostly in heartwood typically require 2–3 or more years to complete one generation (Haack and Slansky 1987). Given the above-mentioned trends, it is understandable that live borers would be present in firewood, especially during the first few years after tree death or cutting.

[1] USDA Forest Service, Northern Research Station, 1407 S. Harrison Rd., E. Lansing, MI 48823.
[2] Corresponding author, e-mail: rhaack@fs.fed.us.
[3] USDA Forest Service, Forest Products Laboratory, One Gifford Pinchot Dr., Madison, WI 52726.

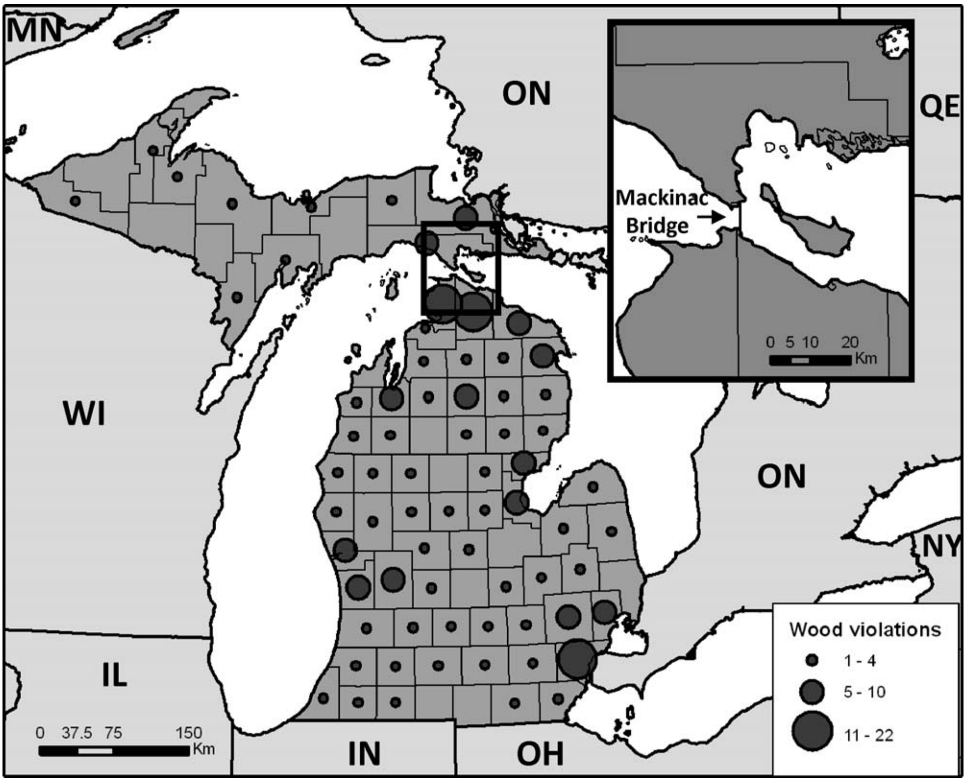

Fig. 1. County outline map of Michigan and nearby U.S. states and Canadian provinces, indicating location of Mackinac Bridge between Michigan's Lower and Upper peninsulas (see inset). Circles represent those Michigan counties that were the source for firewood that was collected from vehicles at the Mackinac Bridge based on 322 driver interviews during 2006–2009. The size of the circle represents the number of driver interviews made for firewood violations that originated from each particular county. Overall, firewood originated from 71 of Michigan's 83 counties, as well as 17 other U.S. states and three Canadian provinces. See discussion. (Illinois, IL; Indiana, IN; Minnesota, MN; New York, NY; Ohio, OH; ON, Ontario; and QE, Quebec).

The emerald ash borer, *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae), is native to Asia and was first discovered in southeastern Michigan and neighboring Ontario, Canada, in 2002 (Haack et al. 2002). *A. planipennis* infests *Fraxinus* (ash) trees in North America and requires 1–2 yr to complete one generation (Cappaert et al. 2005, Poland and McCullough 2006, Anulewicz et al. 2008). Larvae feed in the cambial region of the trunk and branches during summer and then typically overwinter in the outermost centimeter of sapwood. Based on the above-mentioned information, as well as actual field studies (Petrice and Haack 2006, 2007), the risk of moving live *A. planipennis* would be highest during the first year after cutting firewood from currently infested *Fraxinus* trees, and to a lesser degree during the second year. In addition, even bark-free *Fraxinus* firewood could still transport live *A. planipennis*, given that most overwintering and pupation occurs in the outer sapwood.

A federal quarantine for *A. planipennis* was enacted in both Canada and the United States in 2003 (USDA–APHIS 2003; CFIA 2006, 2007) to reduce the likelihood of human-assisted movement of emerald ash borer. These quarantines are still in effect as of 2010 and regulate movement of ash logs, nursery stock, and firewood. In addition to ash firewood being regulated, firewood from all woody species (both conifers and hardwoods) is regulated in Canada, whereas only firewood from hardwood species is regulated in the United States. The reason to regulate firewood beyond the genus *Fraxinus* is because most inspectors and the public cannot differentiate among wood species when examining firewood.

Michigan borders on four of the five Great Lakes and consists of two peninsulas (Lower and Upper) that are joined by the 8-km-long Mackinac Bridge (Fig. 1). From 2002 to 2004, several isolated *A. planipennis* infestations were found in Michigan's northern Lower Peninsula, and most were attributed to movement of infested firewood (Robertson and Andow 2009). Given concerns that *A. planipennis* could easily be transported to the Upper Peninsula, the Michigan Department of Agriculture began a program in March 2005 to collect all firewood being transported in vehicles before or immediately after crossing the Mackinac Bridge. Drivers are informed with signs as they approach the bridge that they must dispose of all firewood in specified collection containers, with failure to do so resulting in possible fines. Unfortunately, an *A. planipennis* infestation was found in Michigan's Upper Peninsula in September 2005 at Brimley State Park, and others have been found in the Upper Peninsula since then (Storer et al. 2009). Nevertheless, as of May 2010, the firewood drop-off program at the Mackinac Bridge was still active.

In early 2008, given broad interest in knowing the incidence of live insects in the firewood collected at the Mackinac Bridge, we contacted personnel in the Michigan Department of Agriculture to plan for multiple firewood surveys in 2008. The objective of this study was to examine firewood that had been recently collected at the Mackinac Bridge to determine what wood species were being moved by the public and to document whether any of the firewood contained live bark- or wood-boring insects, and especially *A. planipennis.*

Materials and Methods

We conducted surveys in April, July, and September 2008. The firewood inspected in early April had been collected during the previous few winter months and stored outdoors. The firewood inspected in early July had been collected primarily from May through early July. Similarly, the firewood inspected in early September had been collected primarily from mid-July through August. In general, we inspected all firewood that had been collected.

We first identified each piece of firewood to tree species or genus based on bark, wood, and growth characteristics. If we were uncertain about the identity, we collected a small wood sample for later microscopic examination at the U.S. Department of Agriculture (USDA), Forest Service, Center for Wood Anatomy Research in Madison, WI. We were able to identify black cherry (*Prunus serotina* Ehrh.) firewood to the species level, but several other genera of Rosaceae (*Crataegus, Malus,* other *Prunus,* and *Pyrus*) were grouped in the category "fruitwood" because generic-level wood identification within the group is not reliable. We categorized the general cross-sectional shape of each piece of firewood as a whole log section if it had not been split, a half section if 50 to <100% or the original cross-sectional area was present, or a quarter section if <50%. We next recorded bolt length, diameter (actual or approximate), approximate percentage of original bark, and approximate age or time since the piece of firewood had been part of a live tree (<1, 1–2, or >2 yr). We estimated the age based on the condition of the bark; the tightness of the bark to the wood; the soundness of the outer sapwood; the kinds and life stages of insects found, or their signs such as larval galleries and exit holes. We next inspected the bark surface for borer exit holes. Later, after removal of all bark, we examined the sapwood and inner bark surfaces for borers and their galleries and exit holes. Next we split each piece of firewood with a log splitter and examined all pieces for borers or their signs. Logs were split numerous times until we were confident that all borers and their signs were noted if present. We generally identified all borers to at least the family level (Triplehorn and Johnson 2005) and recorded their life stage, and whether they were apparently alive or dead. We did not count every individual borer, especially the Scolytinae, and therefore we cannot calculate density values. In addition, we did not differentiate between powderpost beetles in the families Anobiidae and Bostrichidae (Coleoptera) and therefore recorded them both as members of the superfamily Bostrichoidea.

Analyses. We used PROC GLIMMIX (SAS Institute 2006) to compare the frequency that borers were found in firewood pieces from the various bark and log categories. Because the response variable was binary (yes–no), we used a binary distribution with a logit link function to more effectively model the response variable. Least squared means that were significantly different ($P < 0.05$) were compared using the Bonferroni means separation test.

Results

We examined 1,045 pieces of firewood during the three surveys: 186 pieces in April, 389 in July, and 470 in September 2008. Live borers were found in firewood during each survey: 15% of the pieces had live borers in April, 16% in July, and 33% in September (Table 1). Live Buprestidae, Cerambycidae, and ambrosia beetles (Scolytinae) were found during all three surveys, whereas true bark beetles (Scolytinae) were found only during the two summer surveys (Table 1).

The 1,045 pieces averaged (±SE) 41.5 ± 0.3 cm in length (range, 14–91 cm) and 16.9 ± 0.3 cm in diameter (range, 2–45 cm). In cross section, most pieces were whole (47%) or quarter (43%) sections (Table 1). Bark, in any amount, was present on 73% of the pieces (Table 1). Considering all 1,045 pieces, 27% were bark free, 3% had 1–25% of their original bark, 5% had 26–50%, 3% had 51–75%, 8% had 76–99%, and 54% had 100%.

Most firewood pieces were aged as having originated from live trees during the previous year (47%) (Table 1). The firewood represented at least 21 tree genera, including four conifer and at least 17 hardwood genera (Table 1). The range in the estimate for the number of possible hardwood genera is because 13 firewood pieces were identified as fruitwood, which consisted of multiple genera. The eight tree genera that each represented at least 2% or more of the firewood were, in decreasing order *Acer, Quercus, Fraxinus, Ulmus, Betula, Prunus, Pinus,* and *Populus* (Table 1). Overall, live borers were present in 17 of the 21 tree genera (Table 1). Of the four genera that lacked live borers, two had evidence of past infestation (*Morus* and *Ostrya*), whereas the other two genera had no evidence of either current or past infestation (*Salix* and *Thuja*) (Table 1).

Live borers were found in 23% of the 1,045 pieces, and an additional 41% had evidence of previous borer infestation (Table 1). The live borers represented three orders and seven superfamilies or fam-

Table 1. Summary data for 1,045 individual pieces of firewood that were collected from the public at the Mackinac Bridge between Michigan's Lower and Upper peninsulas on three occasions in 2008 by sample period and tree genus of the firewood

Sampling period or wood genus	Pieces of firewood			Shape of firewood in cross section			Pieces with bark (%)	Age (approx. no. years since tree cutting or death, %)			Pieces with evidence of borers[b] (%)	Pieces with live borers (%)	Superfamilies, families, or subfamilies of live borers found in firewood pieces (ranked high to low)[c]
	No.	% total	% MI LP[a]	Whole (%)	Half (%)	Quarter (%)		<1	1–2	>2			
Sample period													
April	186	17.80	NA	56	8	36	76	64	34	2	53	15	CE > BU > AM > CO = CU = SI
July	389	37.22	NA	41	10	50	75	38	47	16	59	15	BB > CE > AM > BO > BU
Sept.	470	44.98	NA	48	13	39	71	48	26	26	73	33	CE > BO > BB > BU > AM > CU = SI > BR
Total	1045	100.00	NA	47	11	43	73	47	35	18	64	23	CE > BO > BB > BU > AM > CU = SI > BR = CO
Wood genus													
Acer	317	30.33	21.85	42	10	48	83	69	26	5	45	15	CE > BU > BO > AM = SI > CO
Betula	54	5.17	1.45	46	28	26	100	26	63	11	61	7	CE > BO
Carya	8	0.77	0.87	38	13	50	88	63	25	12	63	50	CE
Fagus	4	0.38	2.05	50	0	50	100	25	75	0	100	25	CE
Fraxinus	152	14.55	9.55	50	11	39	91	86	14	1	71	31	BB > CE > AM
Fruitwood[d]	13	1.24	1.45	77	8	15	92	62	38	0	85	46	BB
Juglans	11	1.05	0.15	27	0	73	36	9	91	0	18	18	BU > CE
Juniperus	1	0.10	0.07	100	0	0	100	0	100	0	100	100	CE
Morus	8	0.77	0.04	38	13	50	100	37	63	0	63	0	None
Magnolia	2	0.19	0.003	100	0	0	100	0	100	0	50	50	BU
Ostrya	5	0.48	2.01	20	20	60	100	20	80	0	80	0	None
Picea	12	1.15	1.95	17	33	50	92	50	33	17	58	8	CE
Pinus	39	3.73	10.28	49	15	36	56	36	49	15	87	26	CE > CU > BO = BB
Populus	36	3.44	13.57	25	8	67	89	61	33	6	53	11	CE > AM = BO
Prunus	49	4.69	4.60	43	2	55	73	24	57	18	76	18	CE > BB
Quercus	185	17.70	7.46	28	12	59	56	17	55	28	64	11	CE > AM = BR
Robinia	3	0.29	0.13	100	0	0	100	0	0	100	100	33	CU
Salix	2	0.19	0.47	100	0	0	100	100	0	0	0	0	None
Sassafras	11	1.05	0.98	100	0	0	100	73	9	18	91	73	CE > AM
Thuja	1	0.10	5.27	0	0	100	100	100	0	0	0	0	None
Tilia	8	0.77	1.27	0	13	88	88	63	0	37	63	13	CE
Ulmus	124	11.87	3.20	88	6	6	31	4	27	69	97	60	BO > CE > BU > BB > SI
Total	1045	100.01	88.98	47	11	43	73	47	35	18	64	23	CE > BO > BB > BU > AM > CU = SI > BR = CO

[a] MI LP, Lower Peninsula of Michigan. Values represent the relative percentage of all live trees >2.54-cm (1-in.) dimater at breast height (dbh) on forestland based on Forest Service surveys during the last complete 5-yr survey cycle (2003–2007) (USDA FS 2009). NA, not applicable.

[b] Includes any piece of firewood with either live borers, signs of past borer infestation, or both.

[c] Borer families and subfamilies: AM, Scolytinae ambrosia beetles; BO, Bostrichoidea; BB, Scolytinae bark beetles; BR, Brentidae; BU, Buprestidae; CE, Cerambycidae; CO, Cossidae; CU, Curculionidae (non-Scolytinae); SI, Siricidae; None, no live insect borers found.

[d] Fruitwood, the following genera of Rosaceae were combined because they are difficult to differentiate from wood samples: *Crataegus*, *Malus*, *Prunus* other than *P. serotina*, and *Pyrus*.

Table 2. Summary data for the occurrence of live borers or evidence of their past infestation by various attributes of the firewood collected and inspected at Michigan's Mackinac Bridge on three occasions in 2008 (data pooled, $N = 1045$ firewood pieces)

Firewood attribute	No. firewood pieces	% firewood with signs of current or past infestation	% firewood with live borers	Superfamilies, families or subfamilies of live borers found in firewood pieces[a] (ranked high to low)
Cross-sectional shape of firewood pieces				
Quarter section	445	55.7b[b]	11.7b[b]	CE > BB > BU > BO > AM = BR
Half section	113	65.5ab	21.2ab	BB > CE > BU = BO = AM
Whole log	487	71.5a	33.7a	CE > BO > BB > BU > AM > CU = SI = CO
F; df; *P*		12.4; 2, 1,042; 0.0001	29.66; 2, 1,042; 0.0001	
Approximate time since cutting or tree death				
<1 yr	488	47.6c	23.1b	BB > CE > BU > AM > CU > CO = SI
1–2 yr	369	70.9b	15.8c	CE > BO > BU > AM > SI
>2 yr	188	93.6a	36.7a	BO > CE > BU > BR = CU = SI
F; df; *P*		53.39; 2, 1,042; 0.0001	14.83; 2, 1,042; 0.0001	
Presence of bark				
Yes	765	58.6b	22.5a	CE > BB > BU > BO > AM > CU = SI > CO
No	280	79.3a	25.0a	BO > CE > BU > AM = BR
F; df; *P*		36.59; 1, 1,043; 0.0001	0.38; 1, 1,043; 0.5399	

[a] Borer families and subfamilies as in Table 1.
[b] Percent values (within columns and categories) followed by the same letter were not significantly different at the $P < 0.05$ level (PROC GLIMMIX followed by the Bonferroni means separation test of least squared means).

ilies: Coleoptera—Bostrichoidea, Brentidae, Buprestidae, Cerambycidae, and Curculionidae (both Scolytinae and non-Scolytinae); Hymenoptera—Siricidae; and Lepidoptera—Cossidae (Table 1). Live borers in the family Cerambycidae were found in the most tree genera (15), followed by bark beetles (Scolytinae—7), ambrosia beetles (Scolytinae—5), Buprestidae (3), Curculionidae (non-Scolytinae—2), Siricidae (2), Brentidae (1), and Cossidae (1) (Table 1). Moreover, when considering all 1,045 firewood pieces, live Cerambycidae were found in 109 pieces, followed by Bostrichoidea in 60, true bark beetles (Scolytinae) in 55, Buprestidae in 19, ambrosia beetles (Scolytinae) in nine, Curculionidae (non-Scolytinae) in three, Siricidae in three, Brentidae in one, and Cossidae in one.

We found live borers in all cross-sectional shapes of firewood with whole pieces being the most commonly infested (34%) (Table 2). Similarly, live borers were found in all three age classes of firewood, with pieces classified as >2 yr since cutting or tree death being the most infested with live borers (37%) (Table 2). The occurrence of live borers was similar in firewood pieces with or without bark (Table 2). Evidence of current or past borer infestation was significantly higher in whole logs (72%) and in pieces cut >2 yr earlier (94%) (Table 2). As for the occurrence of live bark beetles, they were found in all cross-sectional shapes of firewood (6% of whole, 10% of half, and 4% of quarter sections), but only in pieces that were cut during the previous year (11% were infested with live bark beetles) and only in pieces with bark (7% of the pieces with bark had live bark beetles).

Evidence of infestation by *A. planipennis* (galleries and exit holes) was found in 19 of the 152 pieces (13%) of the *Fraxinus* firewood. Although live borers were found in 31% of the *Fraxinus* firewood (Cerambycidae and Scolytinae; Table 1), no live *A. planipennis* life stages were present. Nevertheless, we did locate two dead *A. planipennis* adults in the outer bark of two separate pieces of *Fraxinus* firewood.

Discussion

Our results indicate that live borers are transported in firewood throughout the year and that practically all tree species used for firewood can harbor live insects. The two tree genera that lacked evidence of borer infestation in our study were each represented by small sample sizes (two pieces of *Salix* and one piece of *Thuja*). Given that several bark- and wood-infesting borers infest these two tree genera in North America (Drooz 1985, Furniss and Carolin 1977, Solomon 1995), we suspect that we would have found some infested *Salix* and *Thuja* firewood if our sample sizes had been larger.

The frequency at which borers were encountered in firewood and the high diversity of families noted in this study were not unexpected given that bark- and wood-infesting insects have evolved to use basically all tree species. In fact, the diversity of borers and other associated organisms that inhabit deadwood has been a topic of great interest within forestry circles in recent decades, especially with respect to biodiversity issues and impacts of forest management activities on saproxylic organisms (Harmon et al. 1986, Siitonen 2001, Grove 2002, Jonsson et al. 2005, Langor et al. 2008).

We do not know the origin of the firewood that we inspected at the Mackinac Bridge given that firewood was commingled once collected. However, we suspect that the majority of the firewood originated from the Lower Peninsula of Michigan and neighboring U.S. states. This contention is supported by summary data from the Michigan Department of Agriculture (MDA, unpublished data) whose employees are stationed at

Table 3. Summary data by year for fuelwood imported into the United States (1996–2009)

Yr	Value (US$)		Countries of origin		U.S. states where imported firewood first entered	
	Total	% CA[a]	No.	Countries (ranked by import value: high to low)[b]	No.	Top 10 states (ranked by import value: high to low)[c]
1996	12,875,836	95.4	10	CA HN ID MX BR NG MY SG FR TW	15	MI NY WA VT FL LA TX AZ CA GA
1997	6,219,924	84.5	8	CA HN MX BR NG SG AR HK	13	MI NY WA MT FL TX LA VT AZ SC
1998	4,101,892	87.4	10	CA MX HN LK AR SG UK GT NG DE	11	MI WA NY TX CA VT MT LA FL AZ
1999	4,248,273	59.7	13	CA LR HN MX JP DE SG NG LK GT CN TW AR	15	WA VA NY MI FL CA LA VT SC MT
2000	4,292,368	82.9	7	CA HN MX SG LK TW AR	16	WA NY ME FL VT MT LA MI AZ CA
2001	4,975,108	81.8	6	CA HN MX SG AR DE	16	WA NY ME MI VT LA SC VA FL MT
2002	6,094,694	66.0	9	CA AR HN MX PY MY SG BR PH	15	WA TX ME NY MI LA FL VT SC MT
2003	6,174,929	73.6	9	CA HN AR MX SG UK LT FR JP	19	WA ME NY VT TX AL LA SC FL MI
2004	8,229,009	72.0	9	CA HN EE BR FR MX VN NG SG	17	WA NY VT ME SC MN FL LA AL ND
2005	8,867,605	74.5	8	CA HN BR EE MX MY AR SG	18	WA NY MN ME VT FL SC TX LA MI
2006	9,037,934	59.9	8	CA HN EE BR MX ID SV SG	18	WA NY FL VT ME AL TX MI CA PA
2007	8,352,697	62.7	10	CA HN EE MX BR CN LK SG CO DO	13	WA NY FL ME VT MI CA AZ TX GA
2008	8,227,092	64.2	12	CA HN EE MX SE AR SG DE LI UK IT AU	13	WA NY FL ME VT TX MI LA CA AZ
2009	7,097,736	48.2	14	CA HN EE LV MX AR SV SE CH ID CN NL CO JP	14	WA NY FL VT CA ME TX LA MI VA
Total	98,795,097	72.6	34	CA HN EE MX BR AR LR SG LV ID LK NG FR MY DE SE JP CN SV UK GT PY TW VN CO CH LT NL DO LI HK IT AU PH	27	(All states) WA NY MI FL ME VT TX LA MN SC CA VA MT AL AZ ND GA PA MA AK IL OR MD OH NC MO WI

Source of data, http://www.usatradeonline.gov/.

[a] Percentage of firewood that was of Canadian origin based on declared value.

[b] Country codes: AR, Argentina; AT, Austria; BR, Brazil; CA, Canada; CH, Switzerland; CN, China; CO, Colombia; DE, Germany; DO, Dominican Republic; EE, Estonia; FR, France; GT, Guatemala; HK, Hong Kong; HN, Honduras; ID, Indonesia; IT, Italy; JP, Japan; LI, Liechtenstein; LK, Sri Lanka; LR, Liberia; LT, Lithuania; LV, Latvia; MX, Mexico; MY, Malaysia; NG, Nigeria; NL, Netherlands; PH, Philippines; PY, Paraguay; SE, Sweden; SG, Singapore; SV, El Salvador; TW, Taiwan; UK, United Kingdom; VN Vietnam.

[c] U.S. States: AK, Alaska; AL, Alabama; AZ, Arizona; CA, California; FL, Florida; GA, Georgia; IL, Illinois; LA, Louisiana; MA, Massachusetts; MD, Maryland; MI, Michigan; ME, Maine; MN, Minnesota; MO, Missouri; MT, Montana; NC, North Carolina; ND, North Dakota; NY, New York; OH, Ohio; OR, Oregon; PA, Pennsylvania; SC, South Carolina; TX, Texas; VA, Virginia; VT, Vermont; WA, Washington; WI, Wisconsin.

the Mackinac Bridge year-round and conduct detailed interviews with as many drivers as possible when they surrender firewood. Overall, based on 322 interviews with drivers who surrendered firewood from March 2006 through October 2009, 75% of the vehicles had firewood that originated from Michigan's Lower Peninsula (242 vehicles from 61 Michigan counties), 7% from Michigan's Upper Peninsula (24 vehicles from 10 counties), 16% from 17 other U.S. states (52 vehicles: IN 15, OH 8, WI 4, IL 3, MN 3, NY 3, PA 3, IA 2, SC 2, TN 2, KY 1, LA 1, NJ 1, NM 1, NC 1, TX 1, and VA 1), and 1% from Canada (four vehicles: Ontario 2, Alberta 1, and Newfoundland 1) (Fig. 1). The dates when these 322 interviews were made indicated that firewood was transported during every month of the year, peaking in July during each of the four years sampled. Other evidence to suggest that most firewood originated from the Lower Peninsula of Michigan is the fact that all 21 tree genera represented by the firewood inspected in this study are common forest trees in Michigan (Table 1; USDA FS 2009).

Although we found that whole pieces of firewood were the most commonly infested category, this finding may simply reflect that whole pieces, on average, contained more wood volume than pieces that had been split into half or quarter sections, and thus were more likely to contain borers. The finding that firewood classified as >2 yr since cutting was the most infested age class was greatly influenced by the large number of *Ulmus* pieces ($N = 49$) that were over 2 yr of age and infested with live Bostrichoidea. If all *Ulmus* firewood were dropped from our analysis, then firewood classified as <1 yr since cutting would have been the most frequently infested age class ($F = 8.27$; df = 2, 918; $P = 0.0003$).

Given that firewood dried for one or more years typically burns hotter and cleaner than green (recently cut from a live tree) firewood, it was surprising that nearly half (47%) of the firewood pieces inspected seemed to have been cut from live trees during the preceding year. This demonstrates, along with the fact that bark was present on 73% of all firewood pieces, that much of the firewood transported by the public could easily contain borers that typically infest live or recently dead trees, including such high-profile exotics as *A. planipennis* (Poland and McCullough 2006), *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae) (Haack et al. 1997, 2010), and *Sirex noctilio* F. (Hymenoptera: Siricidae) (Gilmour 1965).

The result that the incidence of live borers was similar in logs with and without bark probably reflects that most larvae encountered were Cerambycidae, which often have larval developmental periods that extend for one or more years; thus, once larvae enter the wood, bark is usually no longer needed to complete larval development. However, the presence of bark was very important for insects like bark beetles that develop directly under bark, given that bark beetles were found only when bark was present and they were only encountered under bark. Similarly, Haack and Petrice (2009) reported that bark beetle colonization of green lumber after heat treatment was ob-

Table 4. Summary data by country of origin for fuelwood imported into the United States (1996–2009)

Country	Total value of imports for period 1996–2009 (US$)	No. yr of imports (1996–2009)	U.S. states where imported firewood first entered	
			No.	States ranked by import value (high to low)
Argentina	1,487,582	10	3	TX FL NY[a]
Austria	4,456	1	1	IL
Brazil	1,620,836	7	3	NY TX SC
Canada	71,737,517	14	10	WA MI NY ME VT MN MT ND AK LA
China	59,751	3	5	TX NY OR CA WI
Colombia	22,641	2	2	CA TX
Dominican Republic	8,157	1	1	VA
El Salvador	56,235	2	2	LA CA
Estonia	4,626,636	6	5	NY CA MA FL MD
France	89,751	3	2	CA NY
Germany	69,848	4	4	CA TX GA NY
Guatemala	36,830	2	1	LA
Honduras	14,880,849	14	13	FL LA SC AL CA VA TX GA PA NY MI WA NC
Hong Kong	5,759	1	1	MO
Indonesia	184,010	3	2	LA NY
Italy	4,500	1	1	LA
Japan	60,646	3	3	NY CA IL
Latvia	193,076	1	3	NY FL CA
Liberia	844,157	1	1	VA
Liechtenstein	7,139	1	1	TX
Lithuania	13,196	1	1	OR
Malaysia	73,790	3	3	GA SC TX
Mexico	1,929,332	14	4	TX AZ CA MD
Netherlands	8,837	1	1	NY
Nigeria	121,483	5	1	CA
Paraguay	31,147	1	1	FL
Philippines	3,251	1	1	NY
Singapore	268,510	13	1	NY
Sri Lanka	160,105	4	2	CA NY
Sweden	65,325	2	3	CA WA NY
Switzerland	18,042	1	1	NY
Taiwan	27,572	3	2	CA MO
United Kingdom	47,226	3	3	CA OH TX
Vietnam	26,905	1	1	IL
Total	98,795,097	14	27	See Table 3

Source of data: http://www.usatradeonline.gov/.
[a] State abbreviations given in Table 3.

served only on wood pieces with bark, and that all bark beetles were found beneath bark patches.

Although no live *A. planipennis* were found in the *Fraxinus* firewood that we inspected, 13% of the pieces had evidence of past *A. planipennis* infestation. Moreover, when reviewing the 322 MDA reports for firewood that had been surrendered at the Mackinac Bridge during 2006–2009, we noted a few reports where ash firewood from both Lower Peninsula of Michigan and Ohio had *A. planipennis* galleries and exit holes, but no live *A. planipennis* life stages were noted. Such findings indicate the potential for *A. planipennis* to be transported in firewood, and indeed there have been reports in the United States of *A. planipennis* infestations linked directly to firewood movement (McCullough et al. 2004, Robertson and Andow 2009).

The firewood economy is complex, with many companies and individuals involved in harvesting and transporting (producers), packaging and shipping (distributors), selling (retailers), and burning (end users) (Robertson and Andow 2009). There is a formal firewood economy with identifiable companies that treat and transport firewood often among multiple states. There is also an informal firewood economy that is more difficult to identify given that it consists largely of private individuals who usually cut, transport, sell, and burn firewood more locally. In addition, as noted by the MDA interviews with drivers at the Mackinac Bridge, vacationers and owners of second homes often transport firewood long distances that they have either cut themselves or purchased.

In recognition of the risk posed by firewood to forest health, several U.S. states have placed restrictions on out-of-state firewood unless treated. Even within a single U.S. state, people are being encouraged to not move firewood, and instead to buy local firewood when they reach their final destination. Some states consider local to mean within an 80-km (50-mile) radius or within the same county (Robertson and Andow 2009). Educational campaigns on the risks posed by moving untreated firewood have been initiated in almost every U.S. state as well as through national programs and websites, such as http://www.dontmovefirewood.org/.

At the U.S. national level, resolutions have been adopted by the National Association of State Departments of Agriculture (NASDA 2007), National Plant Board (NPB 2007), and National Association of State Foresters (NASF 2009) that endorsed federal involve-

Table 5. Summary data by U.S. state for fuelwood imported into the United States during 1996–2009

State	Total value of imports for 14-yr period (US$)	No. yr of imports (1996–2009)	Countries[a] that exported firewood to the United States	
			No.	Countries ranked by import value (high to low)
Alaska	37,358	3	1	CA
Alabama	974,591	5	1	HN
Arizona	538,518	13	1	MX
California	1,436,732	14	15	HN MX NG LK FR EE DE SE TW SV UK LV CO CN JP
Florida	8,126,472	14	5	HN AR PY LV EE
Georgia	212,641	6	3	HN MY DE
Illinois	33,631	3	3	VN AU JP
Louisiana	2,280,320	12	6	HN ID GT SV IT CA
Massachusetts	45,792	2	1	EE
Maryland	24,086	4	2	EE MX
Maine	6,652,858	14	1	CA
Michigan	14,065,725	14	2	CA HN
Minnesota	2,062,492	6	1	CA
Missouri	7,392	2	2	HK TW
Montana	1,186,821	10	1	CA
North Carolina	15,952	1	1	HN
North Dakota	365,554	8	1	CA
New York	18,372,729	14	17	CA EE BR SG LV HN JP LK ID AR CH CN FR NL SE PH DE
Ohio	20,195	1	1	UK
Oregon	24,235	2	2	LT CN
Pennsylvania	142,974	2	1	HN
South Carolina	1,743,350	10	3	HN BR MY
Texas	3,212,977	14	10	AR MX HN BR CN MY DE LI CO UK
Virginia	1,408,625	10	3	LR HN DO
Vermont	5,291,920	14	1	CA
Washington	30,509,050	14	3	CA HN SE
Wisconsin	2,107	1	1	CN
Total	98,795,097	14	34	See Table 3

Source of data: http://www.usatradeonline.gov/.
[a] Country abbreviations given in Table 3.

ment by the USDA in regulating firewood treatment and interstate movement. Because effectively addressing the firewood pathway involves a range of partners and activities, the USDA Animal and Plant Health Inspection Service (APHIS) formed the National Firewood Task Force (NFTF) in 2009 (NPB 2009), which included state and federal agriculture and natural resource agencies. The NFTF formulated recommendations in 2010 for government agencies, industry, and the general public in the areas of firewood regulation, voluntary best management practices, and educational outreach (NPB 2010).

In addition to the movement of domestic firewood, it is important to note that the United States also imports large quantities of fuelwood (Tables 3–5). Imports of fuelwood in the form of logs, billets, and twigs are recorded under the Harmonized Tariff Schedule of the United States as HTS Code 4401100000 by the U.S. Department of Commerce. These data are available online at http://www.usatradeonline.gov/. For example, during the 14-yr period 1996–2009, the United States imported fuelwood from 34 countries in Africa, Asia, Caribbean, Central America, Europe, North America, and South America, with a total declared value on arrival in the United States of >$US 98 million (Table 3). Overall, ≈73% of the fuelwood imports were from Canada. Imported fuelwood entered through 11–19 U.S. states for any individual year and through 27 states for the combined 14-yr period (Table 3). Fuelwood was imported during each of the 14 yr sampled from only three of the 34 countries: Canada, Honduras, and Mexico (Table 4). Fuelwood from Honduras entered the most U.S. states (13), followed by Canadian fuelwood (10) (Table 4). Of the 27 U.S. states that imported fuelwood during this period, most (31%) entered through Washington (Table 5). There were eight states that imported fuelwood during each of the 14 yr sampled: (high to low) WA, NY, MI, FL, ME, VT, TX, and CA (Table 5). New York imported fuelwood from the largest number of different countries during this period (17), followed by California (15) and Texas (10), with the remaining 24 states importing from one to six countries each (Table 5).

Fuelwood is generally heat treated to a core temperature of 71°C for 75 min before export to the United States (USDA–APHIS 2009), but this is not the case for all countries. For example, the requirement that Canadian firewood be heat treated before entry into the United States began in October 2008, and this regulation is for hardwood firewood only (USDA–APHIS 2008). In addition, fuelwood from the Mexican states that border the United States is allowed entry to the United States once inspected and found to be pest free, with no treatments required (USDA–APHIS 2004).

Firewood has been implicated in the spread of many bark- and wood-boring insects in the United States. For example, *Agrilus prionurus* Chevrolat, was first reported in Texas in 2003 (Wellso and Jackman 2006) and is now causing widespread mortality of western soapberry (*Sapindus drummondii* Hook. & Arn.) in Texas (Billings and Pase 2009). This beetle is native to Mexico and firewood is considered the likely pathway by which it entered Texas (Haack 2006). *Agrilus coxalis* Waterhouse was first linked to widespread oak (*Quercus* spp.) mortality in southern California in 2008, although specimens from California have now been identified that date to 2004 (Westcott 2005, Coleman and Seybold 2008). This species is native to Guatemala, Mexico, and Arizona. In 2009, Hespenheide and Bellamy (2009) removed *A. auroguttatus* from synonymy with *A. coxalis*, and considered it a distinct subspecies: *Agrilus coxalis auroguttatus* Schaeffer. Currently, the Arizona and California populations are both considered to be *A. c. auroguttatus* (Hespenheide and Bellamy 2009). Again, firewood is considered the probable pathway by which *A. c. auroguttatus* moved from either Arizona or northern Mexico to California (Coleman and Seybold 2008). The redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff (Coleoptera: Curculionidae: Scolytinae), which is native to Asia, and its fungal symbiont *Raffaelea lauricola* Harrington & Fraedrich, are highly lethal to redbay, *Persea borbonia* (L.), trees and some related species of Lauraceae in the southeastern United States (Hanula et al. 2008). Movement of infested firewood is suspected in the recent spread of this exotic insect–fungal complex in Georgia and Mississippi (Cameron et al. 2008, MFC 2009).

Data collected during our study, and by others, demonstrate that firewood is a major pathway by which native and exotic wood-infesting insects can spread both within and among countries. Given the threat posed by firewood to forest health, it is clear that many organizations and agencies will welcome the National Firewood Task Force's recommendations (NPB 2010) and advocate for their implementation. Making progress in this area should reduce the likelihood that firewood will continue to be a major pathway for long-distance spread of exotic forest pests.

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