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Review

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Review

Firewood Transport as a Vector of Forest Pest Dispersal in North America: A Scoping Review

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Abstract

Native and nonnative insects and diseases can result in detrimental impacts to trees and forests, including the loss of economic resources and ecosystem services. Increases in globalization and changing human behaviors have created new anthropogenic pathways for long distance pest dispersal. In North America, literature suggests that once a forest or tree pest is established, the movement of firewood by the general public for recreational or home heating purposes is one of the primary pathways for its dispersal. Understanding human perceptions and behaviors is essential to inform the most effective strategies for modifying firewood and pest dispersal by humans. This scoping review seeks to assess trends and gaps in the existing literature, as well as patterns in behavior related to forest pest dispersal through firewood movement in North America. We identified 76 documents that addressed this topic to which we applied inclusion and exclusion criteria to select articles for further analysis. Twenty-five articles met the inclusion criteria and were categorized based on five identified themes: 1) insect incidence in firewood, 2) insect dispersal via firewood, 3) recreational firewood movement, 4) firewood treatments, and 5) behavior and rule compliance. The selected articles show trends that suggest that firewood movement presents a risk for forest insect dispersal, but that behavior can be modified, and compliance, monitoring, and treatments should be strengthened. This scoping review found limited research about western United States, Mexico, and Canada, various insect species and other organisms, regulation and management, awareness, and behavioral dimensions of firewood movement.

Key words: Coleoptera, firewood movement, human behavior, invasive species, regulations

Nonnative arthropods and microorganisms are a global issue affecting forest ecosystems (Liebhold et al. 2017, Fei et al. 2019, Linnakoski and Forbes 2019). Both natural and urban forests suffer forest pest invasions which are often capable of causing severe deleterious impacts (Poland and McCullough 2006, Dodds and Orwig 2011, Sweeney et al. 2019). North America appears to be at a higher risk of invasive forest pest introductions compared to other continents (Niemelä and Mattson 1996, Early et al. 2016, Klapwijk et al. 2016), which could be due, in part, to its high rate of imported goods and rich diversity of forest types. Nonnative forest pest introductions can result in devastating ecological impacts to forests, including deterioration of ecosystem services, loss of live biomass, changes to forest structure, and loss or changes to forest resources such as wildlife habitat and timber (Boyd et al. 2013, Freer-Smith and Webber 2017). Economic impacts from nonnative forest pests are estimated to be between $4.2 billion and $14.4 billion per year (Pimentel et al. 2000, Holmes et al. 2009, Moser et al. 2009; Table 1). For example, the emerald ash borer (EAB; *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae)), has killed hundreds of millions of ash trees in North America since its introduction in 2002 (Duan et al. 2018), resulting in costs of over $10.7 billion annually (Kovacs et al. 2010). The projected economic impacts of the Asian longhorned beetle (ALB; *Anoplophora glabripennis* Motschulsky (Coleoptera: Cerambycidae)) establishing in Canada could be as high as CDN$12 billion annually (Pedlar et al. 2020).

How insects disperse has been the subject of entomological research for decades (Stinner et al. 1983) and has major implications for the broader topic of invasive species movement and insect dispersal via the movement of firewood. Although forest pests can spread naturally, increases in globalization and human-mediated pathways (i.e., transport of pests in infested goods and transport of contaminated conveyances such as shipping containers and pallets; Gippet et al. 2019, Meurisse et al. 2019) have created new pathways for their rapid dispersal across and between continents (e.g., Short et al. 2020).

Table 1. Major native and nonnative insect species in North America that can spread via firewood, their distribution, and their impact assessed by basal area losses (Krist et al. 2014, Karel and Man 2017, NRCan 2018)

Insect	Scientific name	Origin	Distribution		Basal area losses (m^2/ha^2)[a]
			United States	Canada	
Gypsy moth[b]	*Lymantria dispar dispar* L.	Non-native	Northeast	Southeast	338.2
Emerald ash borer	*Agrilus planipennis* Fairmaire	Non-native	Northeast	East	77.7
Redbay ambrosia beetle	*Xyleborus glabratus* Eichhoff	Non-native	Southeast	Not detected	300[c]
Asian longhorned beetle	*Anoplophora glabripennis* Motschulsky	Non-native	East	East (Ontario)	0.12[d]
Mountain pine beetle	*Dendroctonus ponderosae* Hopkins	Native	Midwest & West	Southwest	215.8
Southern pine beetle	*Dendroctonus frontalis* Zimmermann	Native	East	Not detected	197.3
Spruce beetle	*Dendroctonus rufipennis* Kirby	Native	Midwest & Alaska	West (British Columbia)	163.4
Douglas-fir beetle	*Dendroctonus pseudotsugae* Hopkins	Native	West	West (British Columbia)	139.5

It should be noted that while a scenario with no control of ALB populations could be catastrophic, aggressive eradication protocols do exist and are employed for this particular pest, and these activities keep damage relatively low compared to other forest pests.

[a]Measured in millions.

[b]Risk of being moved in firewood only during egg life stage (Coleman et al. 2020).

[c]Million trees, not basal area (Hughes et al. 2017).

[d]Does not include losses from the current infestation in South Carolina.

This is particularly alarming for wood-inhabiting insects because they can be transported and survive in wood packaging material, logs, wood items, containers, live plants, and vehicles (Liebhold et al. 2012, Meurisse et al. 2019). For example, EAB flight is estimated at only a few kilometer per day (Taylor et al. 2007); however, in 2002, it was found over 9,800 km from its native range. International trade facilitated EAB's accidental introduction to North America, likely through infested wood packaging material (Petrice and Haack 2006, Robertson and Andow 2009, Roy et al. 2014), where it then readily spread via human activities. As such, recent forest pest research has increased attention on forest and tree-inhabiting insects, their rapid spread, and their impacts on natural and managed forests (Table 1; Krist et al. 2014, Karel and Man 2017).

Recreational firewood movement by the general public is considered to be one of the primary means by which wood-inhabiting insects are transported intracontinentally to new areas, serving as an important human-mediated pathway for forest insect dispersal in North America (e.g., Cappaert et al. 2005, Bigsby et al. 2011). After live plants and wood packaging material, firewood logs could be the third most important pathway by which invasive forest insects are transported to other areas (Meurisse et al. 2019). Wood packaging material was likely the pathway by which EAB was introduced to North America, but firewood was been linked to new EAB infestations in the United States (Robertson and Andow 2009). The use of wood as a fuel source dates back thousands of years, but even after industrialization, wood has continued to serve this purpose in North America (U.S. Energy Information Administration 2020). Approximately 6% of Canada's household energy came from wood in 2011 (Statistics Canada 2012) and approximately 2% of residential energy in the United States comes from wood (U.S. Energy Information Administration 2020). In Mexico, firewood is an energy source for 80% of rural communities (CONAFOR 2013). In addition to residential use of firewood for ambiance or as a heating source, recreational use of firewood (e.g., campfires, outdoor cooking) is prevalent across North America (Bratton et al. 1982, Jacobi et al. 2011). Up to 47% of U.S. residents annually burn firewood outdoors for recreational purposes (Solano et al. 2020).

Firewood movement among and within North America is regulated by federal, state, tribal, and local governments. The Canadian Food Inspection Agency (CFIA), United States Department of Agriculture Animal and Plant Health Inspection Service (USDA APHIS), and the National Forestry Commission of Mexico (CONAFOR) work to prevent forest pest introductions and dispersal through firewood movement; however, regulations are limited. The regulations governing the movement of firewood across international borders are similar across the three North American nations' border authorities and focus on prohibiting untreated firewood from entering a country from a neighboring country (e.g., into United States from Canada; Greenwood 2020). In Canada, the Plant Protection Act applies domestically to prohibit the movement of firewood between regulated and nonregulated areas. There are also Canadian regulations in place and enforced by Parks Canada units and Canadian Provinces such as the Yukon's Forest Resources Act, Alberta's Forests Act, Saskatchewan's Forest Resources Management Act, Manitoba's Forest Health Protection Act, and Ontario's Invasive Species Act (Gagné et al. 2017). Firewood regulations for commercial and personal firewood movement in the United States vary significantly across authority and jurisdiction, ranging from no applicable state or federal regulations, to regulations held by states, tribes, land owning federal agencies, to USDA APHIS-regulated pest quarantine areas (e.g., around active infestations of federally regulated pests such as ALB) and other entities. CONAFOR prevents untreated firewood from the United States or Canada from entering Mexico (Greenwood 2020).

The effectiveness of quarantines and/or regulations on firewood has been historically limited due to a combination of factors including inconsistent regulations across geographies and authorities, ineffective surveillance, lack of enforcement (Lovett et al. 2016), and both intentional and unintentional noncompliance (Haack et al. 2014). Additionally, firewood related quarantines and requirements in the United States have had their effectiveness limited due to a history of implementation of regulations postintroduction (Roy et al. 2014). For example, the USDA APHIS regulatory structure means a commodity (such as firewood) in interstate commerce cannot be regulated unless it is designated as a regulated item as part of the response to a federally regulated pest, such as ALB or EAB. Therefore, only reactive—not preventative—federal measures can be implemented. There cannot be a federal regulation that applies to firewood without a federally regulated pest that can infest that firewood, and one cannot apply that regulation outside of the given pests' specific regulated area. This structure is why, for instance, hardwood firewood cannot be legally certified as heat-treated to the applicable federal standard (T-314a) if it is not harvested in an area under federal quarantine for EAB.

There are three generally accepted levels for the international and national heat treatment levels of solid wood products, including firewood. In the United States, the USDA has established heat treatment standards for wood products, including firewood. Heat treatments designated as T314-a, b, and c require solid wood products like firewood to be heated to high temperatures for set periods of time to kill organisms present in or on the wood (USDA APHIS 2010). The International Plant Protection Convention (IPPC) implemented the International Standards for Phytosanitary Measures No. 15 (ISPM-15) which requires an approved treatment (one of the approved heat treatments is the same temperature and duration as USDA T314-b) to eliminate wood-inhabiting insects from wood packaging material (Haack and Petrice 2009). ISPM-15 provides international regulations for effectively treating solid wood packaging so that it poses minimal risk of moving unwanted pests (Wang et al. 2011, FAO 2017). Kiln drying is a process that seeks to reduce the moisture content within the wood; however, it is not a regulated treatment and, therefore, is not permissible as a legal standard to move firewood (Greenwood 2014).

Current pest and firewood regulations have limitations in terms of their efficacy and reach, and their effectiveness relies on sustained awareness and compliance levels of this issue among the firewood-using public. The movement of firewood and the impacts of this behavior could be dramatically reduced if current rules and regulations were followed (Peterson and Diss-Torrance 2012, 2014; Daigle et al. 2018; Diss-Torrance et al. 2018). However, there are various reasons why people do not adhere to rules and regulations, including perceptions of entitlement and fairness (e.g., entitled people are prone to believing they are more deserving of special treatment; Zitek and Jordan 2019). As such, understanding human perceptions and behaviors related to firewood use is essential to inform the most effective strategies for modifying human-mediated firewood and pest dispersal. Nongovernment organizations, like The Nature Conservancy (TNC), play a key role in partnerships with federal, state, provincial, and university entities in conducting long-term research and education for the public in this field. Many national, state, or provincial educational campaigns have been implemented to create awareness among the public about the risk of forest pest dispersal through the movement of firewood. TNC's Don't Move Firewood (DMF) campaign (https://www.dontmovefirewood.org/) is one of the longest standing outreach programs in place aiming to understand and educate people, and change their behavior toward the use of recreational firewood (Campbell 2011).

The preventative policies regulating global trade will never completely remove the risk of accidental pest transport. Additionally, given that the movement of firewood for structure heating and recreational use is an established cultural norm despite existing outreach and regulations, the risk of invasive species movement into and within North America remains high (Haack et al. 2010, Jacobi et al. 2011, Meurisse et al. 2019). Since firewood is known to be a major vector for the spread of wood-inhabiting insects, our objective is to assess the trends and gaps in the existing literature on firewood and forest pest movement in North America, including determining patterns in firewood movement behavior. This assessment will help inform recommendations to help guide future research and education efforts for the public.

Methods

Scoping reviews are assessments of available literature on a given topic to identify data within that literature that can be mapped and synthesized to advance the understanding of that topic (Arksey and O'Malley 2005, Pham et al. 2014). Specifically, scoping reviews pinpoint relevant aspects of the literature such as key concepts, study designs, sources, methodologies, and analyses (Arksey and O'Malley 2005). This scoping review will assess trends, patterns, and gaps in the literature and provide key information to researchers, policy makers, the general public, and government and nongovernment organizations to inform future management and policy decisions related to firewood and pest movement. The five-step methodology outlined by Arksey and O'Malley (2005) was used in the development and implementation of, and as a framework for, these results.

Step 1: Identifying the Research Questions

Available literature shows the main focus of past research on forest pests related to dispersal through firewood movement has been largely limited to the survival, spread (both natural and human-mediated), establishment, treatments, and associated consequences of only a few economically or ecologically important insect species. The focus of this scoping review was firewood because of its importance as a vector for forest pests. The overarching research question that guided this review was: What are the patterns, trends, and gaps associated with the peer-reviewed literature associated with human-mediated dispersal of insects via firewood and its management?

Step 2: Identifying Relevant Articles

The primary method used to find relevant articles was searching electronic databases for literature associated with the topic. The five databases we used were JSTOR, Web of Science, Google Scholar, Agricola, and BioOne. Search terms were entered in the electronic databases using multiple combinations and Boolean operators. We used a total of 26 search terms (Table 2) from six categories for our search: 1) organism, 2) order, 3) family, 4) dispersal, 5) monitoring, and 6) other. It is important to note that the algorithm for Google Scholar changes periodically, causing search results to vary slightly;

Table 2. Categories and search terms used to find literature on forest pests and their dispersal through firewood movement in electronic databases

Category	Organism	Order	Family	Dispersal	Monitoring	Other
Search term	Pest*	Coleoptera	Siricidae	Spread	Regulat*	Firewood
	Insect*	Hymenoptera	Curculionidae	Mov*	Manag*	Forest
	Human*	Lepidoptera	Buprestidae	Transport*	Compliance	Heat treatment
	Fungi		Cerambycidae	Vector	Law*	
	Disease*		Scolytinae	Incidence		
				Pathway		

Asterisks denote a Boolean operator that will include alternative forms of the given word in the search.

as such we accessed the database multiple times between October 2019 and July 2020 to conduct the search. We supplemented our database search with the literature cited sections from selected articles and a short list of relevant research articles and government publications from the DMF webpage (https://www.dontmovefirewood.org/publications-on-firewood-movement-and-human-behavior/).

Step 3: Study Selection

The search process generated a total of 76 documents related to forest pests and firewood. Applying inclusion/exclusion criteria (Table 3), we excluded 52 of the 76 documents. Non-peer-reviewed documents were excluded (19), most of which were government agency publications, books, abstracts, university documents, and articles from nonpeer reviewed journals. Articles resulting from research activities that were conducted outside of North America were also excluded (7). Finally, 26 documents whose focus was not firewood as a vector of insect dispersal were also excluded. These articles focused on topics such as other vectors (i.e., live plant imports, global trade, and wood packaging material), insect biology, global warming implications on invasive species spread, policy, and human health implications. In total, 24 research articles met the inclusion criteria (i.e., peer-reviewed, North American focus, and firewood as a vector of invasive species spread) and were the focus of this scoping review.

Step 4: Charting the Data

We selected 15 key components that allowed for the synthesis and interpretation of relevant information of the selected articles (Table 4). This information is the focus of our study. The selection of these components was guided by previous scoping reviews involving forest pest management as well as consideration of the various components of our selected articles. We developed an Excel sheet with the 15 components of each article to create the themes and categorize the articles into each theme. Organism(s) of study, study keywords, objectives of the study, and important results were the main components guiding this process.

Results

Step 5: Collating, Summarizing, and Reporting the Results

Years of Study and Publication

The 24 articles selected for this scoping review were published between 2006 and August of 2020, half (13) of which were published between 2009 and 2014 (Fig. 1). Research for most of the articles (18) was conducted between 2003 and 2014. Only a single article began data collection in 2002 (Petrice and Haack 2006), and only two articles began data collection after 2014 (Diss-Torrance et al. 2018, Meurisse et al. 2019).

Study Locations

Most of the research activity occurred in the northeastern and midwestern United States (18), with research from five articles being conducted in Michigan (Petrice and Haack 2006, 2007; Poland et al. 2008; Myers et al. 2009; Haack et al. 2010) and research from four articles being conducted in Wisconsin (Tobin et al. 2010; Peterson and Diss-Torrance 2012, 2014; Diss-Torrance et al. 2018). Several research activities were conducted in the western United States, especially the southern Rocky Mountains. Only 4 of the 24 were conducted in Canada, 2 (Barlow et al. 2014, Ali et al. 2015) in Ontario, 1 (Morrison et al. 2016) in Nova Scotia, and 1 (Koch et al. 2014) in most of southern Canada (Fig. 2).

Organisms of Focus

The organisms of focus in the 24 articles selected were either forest insect species or humans, with a major focus on campers. Of the 24 articles, 14 had forest insects as their organism of focus; seven focused on EAB (BenDor and Metcalf 2006; BenDor et al. 2006; Petrice and Haack 2006, 2007; Poland et al. 2008; Myers et al. 2009; Goebel et al. 2010), three (Jones et al. 2013, Mayfield et al. 2014, Morrison et al. 2016) focused on other species (i.e., beech leaf-mining weevil, *Orchestes fagi* L. (Coleoptera: Curculionidae); goldspotted oak borer, *Agrilus auroguttatus* Schaeffer (Coleoptera: Buprestidae); walnut twig beetle, *Pityophthorus juglandis* Blackman (Coleoptera: Curculionidae: Scolytinae)), and four (Haack et al. 2010, Tobin et al. 2010, Jacobi et al. 2012, Dodds et al. 2017) were not species-specific. Nine of the 24 articles studied human populations and their firewood transportation behavior; eight of these focused specifically on campers (Koch et al. 2012, 2014; Peterson and Diss-Torrance 2012, 2014; Barlow et al. 2014; Ali et al. 2015; Daigle et al. 2018; Diss-Torrance et al. 2018), while the ninth addressed humans on a broader scale (Meurisse et al. 2019). Only Jacobi et al. (2011) addressed both forest insects and humans (campers).

Journals

The selected articles were published in 14 different journals (Table 5), with the Journal of Economic Entomology as the most frequent source. Most, but not all, other journals were in the fields of forestry and entomology.

Study Methodologies

Based on the methods section of the articles, it was determined that 23 of the 24 articles used quantitative methodologies, while only Meurisse et al. (2019) was a review article. The quantitative methodologies employed in the selected articles included social science surveys and predictive mathematical models (Table 6).

Key Themes Identified in the Literature

Theme 1 is comprised of articles that address the presence of insects in firewood that was collected, confiscated, bought, or treated. Articles in theme 2 focused on insect dispersal via firewood; these

Table 3. Selection criteria for the articles included in a scoping review related to forest insect pest dispersal through the movement of firewood

Category	Include if:	Exclude if:
Type of literature	It is a peer-reviewed research study	It is not a peer-reviewed research study
Location	The study was conducted in North America	The study was conducted at a location different from North America
Vector	The focus of the study was firewood as vector for invasive insect dispersal	The focus of the study did not include firewood as a vector of invasive insect dispersal

articles help explain the role of firewood as a vector for the spread of invasive forest pests. Theme 3 includes articles that address recreational firewood movement, either by examining camper's behavior and decisions or by modeling them to assess the risk of forest pest spread. Articles in theme 4 evaluate the efficacy of firewood treatments (e.g., heat treatments, plastic bags) to prevent insect emergence from firewood. Theme 5 includes articles that examine behavior and rule compliance of firewood users, most of which were campers; these articles identify the factors (i.e., cost, convenience, quality) that influence camper's decisions to comply with firewood regulations, the efficacy of educational campaigns, and possible strategies to modify camper's compliance and decision (e.g., firewood cost).

Seventeen of the 24 articles were categorized into a single theme; however, eight articles (Poland et al. 2008, Goebel et al. 2010, Jacobi et al. 2011, Jones et al. 2013, Barlow et al. 2014, Mayfield et al. 2014, Ali et al. 2015, Daigle et al. 2018) addressed multiple themes simultaneously. Jacobi et al. (2011) was categorized in themes 1 and 3 as the article addresses both insect incidence in firewood and recreational firewood movement. Four other articles (Poland et al. 2008, Goebel et al. 2010, Jones et al. 2013, Mayfield et al. 2014) were categorized as theme 1 and 4 given that all four articles address insect incidence in firewood and firewood treatments. Three articles (Barlow et al. 2014, Ali et al. 2015, Daigle et al. 2018) were categorized in themes 3 and 5 as they all address recreational firewood movement and behavior and rule compliance.

Table 4. Key items charted from selected articles for a scoping review related to forest insect pest dispersal through the movement of firewood

Variables
Article title
Author(s)
Journal
Year(s) the study was conducted
Year the article was published
Study location
Organism(s) of study
Vector
Study keywords
Objectives of the study
Important results
Causing factors for important results
Study methodology
Population of interest
Gaps

Results by Theme

Theme 1: Insect Incidence in Firewood

Eleven (Petrice and Haack 2006, 2007; Poland et al. 2008; Goebel et al. 2010; Haack et al. 2010; Jacobi et al. 2011, 2012; Jones et al. 2013; Mayfield et al. 2014; Morrison et al. 2016; Dodds et al. 2017) of the 24 articles comprise theme 1, with a focus on insect incidence in firewood that was confiscated, purchased, or cut. Four (Poland et al. 2008, Goebel et al. 2010, Jones et al. 2013, Mayfield et al. 2014,) of the 11 are also in theme 4 and one (Jacobi et al. 2011) is also in theme 3.

Important findings in this theme include insect incidence in examined firewood and insect emergence in firewood logs years after firewood is cut. Haack et al. (2010) investigated insects in confiscated firewood at Michigan's Mackinac Bridge (a point of entry to an EAB quarantine area) and found 1,045 firewood pieces being transported over a 3-mo period, of which 23% had live borers and 41% had evidence of previous insect infestation. Jacobi et al. (2011) collected firewood from several National Parks in the western United States and found that more than half of the firewood had evidence of current or previous insect and/or fungal infestation. Jacobi et al. (2012) found that 50% of national retail firewood and 47% of regional retail firewood had evidence of current or previous insect infestation.

Jacobi et al (2012) observed that some species emerged from firewood up to 558 d after the firewood was purchased (Jacobi et al. 2012; it should be noted that this study was conducted in the southwestern United States where certified heat treatment of firewood did not exist at the time of the study). Further, Goebel et al. (2010) found some EAB emerged from firewood even after heat treatment (46 and 56°C for both 30 and 60 min). These studies suggest that the risk of moving invasive insect pests through firewood remains high even years after the firewood is split (Petrice and Haack 2007, Dodds et al. 2017) and after treatment (Goebel et al. 2010).

Theme 2: Insect Dispersal via Firewood

Theme 2 is comprised of only three articles. BenDor et al. (2006) and BenDor and Metcalf (2006) modeled EAB spread and examined different control methods, whereas Meurisse et al. (2019) reviewed

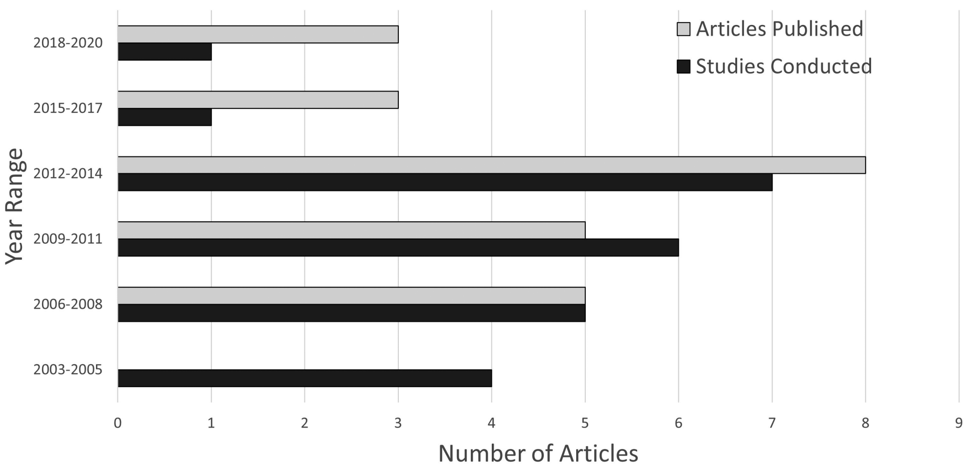

Fig. 1. Frequency of the 24 selected articles by the year(s) in which the study was conducted and published.

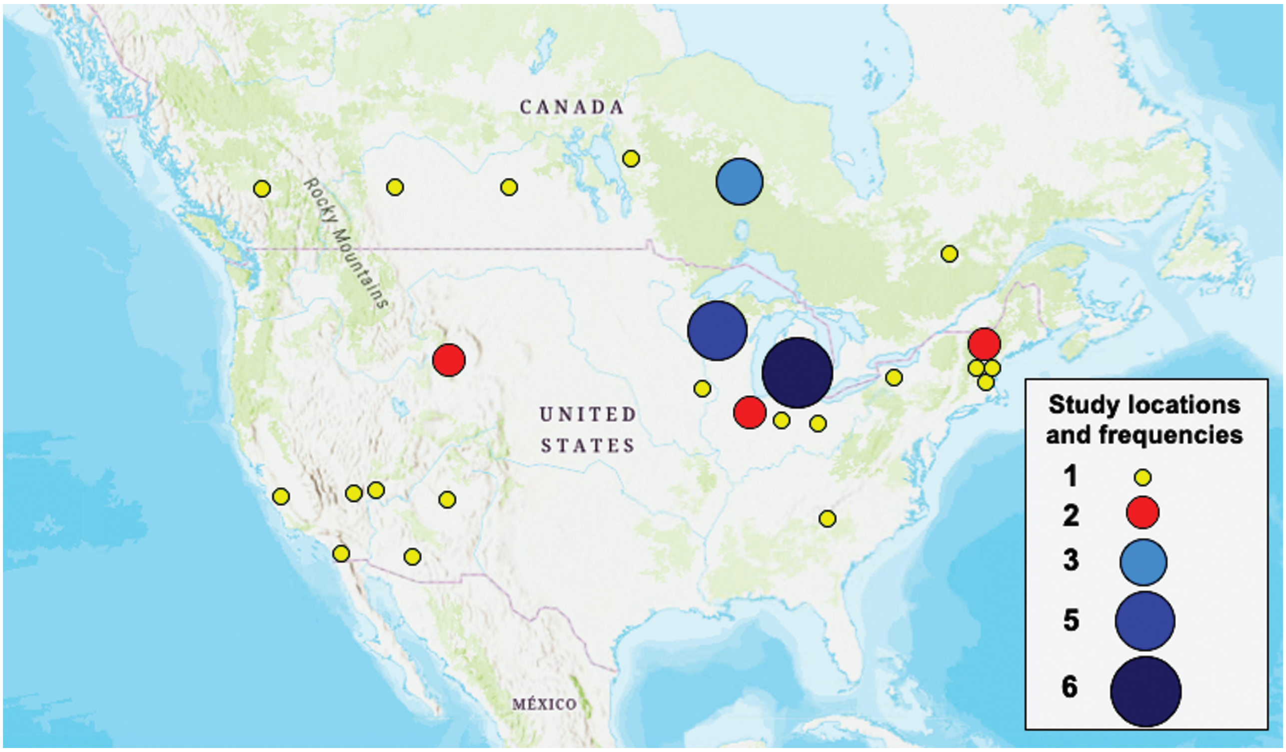

Fig. 2. Location and frequency of research locations from the 24 articles used in this review. The total research locations (40) is greater than the number of articles because the research from some articles was conducted in multiple locations.

the multiple human pathways for insect pest dispersal. BenDor et al. (2006) developed simulation models to compare EAB spread with and without firewood quarantines and found that EAB spread was slower in quarantine models. BenDor and Metcalf (2006) compared three reactive management strategies (i.e., firewood quarantines, ash tree removal, and eradication) using EAB-spread simulations and concluded that preventive measures appear to be more successful than reactive measures and that firewood quarantines were a more effective approach. Both articles concluded that when humans create a dispersal pathway through firewood movement, EAB spreads much faster and has a broader reach.

Meurisse et al. (2019), the only review article selected in this scoping review, indicated that the order Coleoptera, followed by Hymenoptera, Isoptera, and Orthoptera, have the highest frequency of unintentional transport via human-mediated firewood movement. In addition to focusing on firewood, this article also discusses other vectors for invasive insect pest dispersal.

Theme 3: Recreational Firewood Movement

Seven articles were categorized into theme 3, all of which focus on recreational firewood movement, mostly by campers. Jacobi et al. (2011) found that 39% of campers in five western U.S. states brought out-of-state firewood to State or National Parks and some of the firewood in question had evidence of previous or current insect infestations. In addition, only 32% of the firewood assessed in a given National Park had been purchased inside the park (Jacobi et al. 2011). Daigle et al. (2018) also surveyed campers and found that 72% did not transport firewood from home in the case of the specific trip during which the study was conducted. Koch et al. (2012) surveyed campers throughout the United States to find their travel distance to either state or national parks with the goal of showing the potential spread reach if these campers traveled with infested firewood; the median travel distance for campers was close to 100 km and the average was around 236 km, indicating a high potential for pest spread via campers' firewood.

Koch et al. (2014) identified two factors that led to an increased risk of pests in firewood being moved into a new state or province: 1) firewood originating from high-risk regions adjacent to the target state, and 2) major urban areas or pest 'hotspots' outside the state. In addition, Tobin et al. (2010), Barlow et al. (2014), and Ali et al. (2015) included simulation models that provided useful information for potential management strategies to decrease or slow invasive insect spread. Tobin et al. (2010) conducted simulations to determine the risk of infection for campgrounds based on nonnative insect species distribution and allowable distance for firewood movement, and they recommended adjusting firewood movement regulations (allowable distance) as the distribution of the pest species increases. Barlow et al. (2014) and Ali et al (2015) conducted simulation models of firewood transport with scenarios that included a slight increase in infestation concern among the public, and a small decrease in local firewood cost.

Theme 4: Firewood Treatments

Theme 4 included five articles which focus on different firewood treatments for different forest insect pests. Three articles focus on EAB, two of which used ISPM-15 heat treatments for EAB in firewood, while the other two articles address other treatments for forest pests.

Goebel et al. (2010) found that while the application of the minimum internal temperature of ISPM-15 (56°C) did reduce EAB emergence in the firewood, no treatment in their study was completely effective in eliminating all EAB. Myers et al. (2009) found that a minimum internal temperature of 60°C for at least 60 min or 65°C for at least 30 min was required to eliminate EAB, and Poland

Table 5. Journals in which the 24 articles selected for a scoping review related to forest insect pest dispersal through the movement of firewood were published

Journal	Number of articles
Journal of Economic Entomology	9
PLOS ONE	3
Environmental Management	2
The Great Lakes Entomologist	2
Agricultural and Forest Entomology	1
Arboriculture and Urban Forestry	1
Ecological Modeling	1
Forest Science	1
Forests	1
Journal of Pest Science	1
System Dynamics Review	1
The Canadian Entomologist	1
Total	24

Table 6. Methodology used in the articles selected for a scoping review related to forest insect pest dispersal through the movement of firewood

Methodology		Number of articles
Quantitative	Biological	11
	Social Science	9
	Combined	1
Review		1

et al. (2008) found that when ash firewood logs were double bagged with 4-mm thick plastic bags, the beetles died in the bags.

Jones et al. (2013) evaluated several treatments, including solarization, grinding, and debarking, to eliminate goldspotted oak borer larvae from firewood, and found that grinding and debarking were most effective as possible sanitation measures. Mayfield et al. (2014) evaluated heat treatments and debarking of firewood logs to eliminate the walnut twig beetle; results of this study showed that a temperature of 56°C for at least 40 min was an effective treatment to eliminate this insect from firewood.

Theme 5: Behavior and Rule Compliance

Theme 5 is comprised of six articles that focus on the human dimensions of firewood movement by campers. Two articles address camper behavior and strategies while the other two deal with campers' motivations for rule compliance related to firewood movement. Diss-Torrance et al. (2018) surveyed campers at a state park in Wisconsin over a 10-yr period to assess the efficacy of a firewood educational program and found that camper compliance to firewood movement improved after the implementation of an educational program if the message and information were persistently communicated. Daigle et al. (2018) found that of the 28% of campers who transported firewood from home in the case of the specific trip during which the study was conducted, the most common reason for doing so was cost, convenience, and quality. Further, the campers themselves suggested that showing more of the negative impacts of invasive forest insects in outreach and educational materials could help modify camper behavior (Daigle et al. 2018).

Barlow et al. (2014) found that a slight increase in infestation concern among the public, in addition to a small decrease in local firewood cost, is predicted to be enough to increase the proportion of people who help to reduce insect spread by buying local firewood. Based on their simulation models, Ali et al. (2015) suggested that modest increases in tree removal and public concern for insect spread combined with modest decreases in local firewood cost could be a successful strategy.

The other two articles in this theme examine four constructs (i.e., calculated motivation, normative motivation, social motivation, and ability to comply) that influence recreational firewood transport behavior and compliance. Peterson and Diss-Torrance (2012) found that calculated motivations (i.e., price, convenience, quality) have the greatest influence over a camper's decision to comply with firewood regulations. Peterson and Diss-Torrance (2014) also confirmed the strong influence of calculated motivations and found that normative and social motivations have an influence on rule compliance.

Gaps and Limitations

This review has revealed several gaps in the primary literature addressing forest insect dispersal through the movement of firewood and highlights that fact that our understanding of the prevalence, impacts, and management of this pathway is limited. Consistent regulations, monitoring of firewood movement, and firewood treatments are key components for reducing the movement of invasive tree pests. Our review shows that evaluating the success and/or presence of firewood regulations and monitoring of firewood movement is one of the major gaps in our knowledge. No articles directly address the existing regulations on preventing firewood movement. Only one article provides information on insect incidence in firewood collected while entering a quarantined area, as well as rough estimates of how much firewood was being transported at given times of the year past this entry point; however, none of the selected articles address the effectiveness or enforcement of these quarantines. In addition, only six of the 24 articles selected addressed human behavior and rule compliance. Further, while it is a logical assumption that cost of firewood influences rule compliance, and firewood movement in general, only four of those six article addresses this topic (Peterson and Diss-Torrance 2012, 2014; Barlow et al. 2014; Ali et al. 2015). Likewise, how far campers travel, and where they are traveling from and to may also influence behavior; although thus far there is little information on this in the literature. Having a better understanding of why firewood users behave the way they do, and identifying possible ways to modify their behavior, is key to developing successful management and outreach strategies.

Currently, no primary literature addresses the public's awareness of invasive species spread via firewood. This is a key, unexplored, aspect in the literature, given that rule compliance will remain low and behavior will likely not change if the public is not aware that there is an issue. National and regional surveys conducted by The Nature Conservancy revealed that up to 81% of respondents were unaware of laws and regulations preventing firewood movement. Further, 61% had not seen any information urging the public not to move firewood (Solano et al. 2020). As such, research addressing awareness is key for further research in behavior, rule compliance, policy, and management.

While forest pests are a serious concern to North American forests, dispersal of many such species through firewood is understudied. The species that has received the most focus is EAB given that its rapid spread and extensive tree mortality in urban and natural forests is one of the main reasons for the awareness and rise in research on the issue of forest pest dispersal via firewood. However, other insect species—both nonnative and native—that cause damage and/or are continuing to spread (e.g., gypsy moth, *Lymantria dispar dispar* L., Lepidoptera: Erebidae; spotted lanternfly, *Lycorma delicatula*

White, Hemiptera: Fulgoridae; redbay ambrosia beetle, *Xyleborus glabratus* Eichhoff, Coleoptera: Curculionidae: Scolytinae; ALB, and goldspotted oak borer) have not been given nearly as much attention in the peer-reviewed literature, either because they are already very common or because discovery of their invasiveness has been too recent for significant amounts of research to have yet occurred. We also do not know how the potential protection firewood provides insects that may be transported inside might impact pest movement, particularly in light of our changing climate. Wood can act as a temperature buffer to insects, keeping internal wood temperatures up to 4°C warmer than external (Vermunt et al. 2012). Some forest pests have a high thermal plasticity, allowing them to survive a range of temperatures (Sobek et al. 2011), which might further increase their ability to tolerate suboptimal conditions. How might climate change interact with insect physiology, phenology, and development (including emergence) is unknown, likely depends on both the insect and host species, and further underscores the importance of the firewood pathway. Further, since there has been a focus on insects in the literature, other macro (e.g., mites) and microorganisms (e.g., pathogens) have largely been unaddressed, thus their exclusion in our review. Organisms that also cause damage to forest trees like mites and pathogens can also be transported via firewood (Jacobi et al. 2011, 2012), so future research could address this gap.

Most of the research (80%) featured in this review was conducted in the United States and the majority of that (70%) was conducted in the northeastern region of North America, likely because this region has experienced the highest rate of invasion of forest insects (e.g., EAB, ALB, gypsy moth; Liebhold et al. 2013) and high use of firewood for home heating and recreation (U.S. Energy Information Administration 2014). Thus, we lack critical knowledge with regards to forest pests and firewood from several regions of North America (Fig. 2) even though invasive insects are established in these areas. Specifically, the southeastern and northwestern United States, western Canada, and Mexico have a dearth of research attention. As a result, we know little about interactions between native and invasive forest pests and firewood in these regions even though many significant forest pests are prevalent. For example, *Ips* bark beetles, southern pine beetle (*Dendroctonus frontalis* Zimmermann (Coleoptera: Curculionidae: Scolytinae)), and redbay ambrosia beetle can all be moved in firewood in the southeastern United States, yet we know very little about these species' spread via firewood. In summer 2020, ALB was found infesting trees in South Carolina, the first time the species has successfully established in southeastern forests. While it is unlikely the pathway for ALB into South Carolina will ever be definitively determined, it is certainly plausible that firewood may have played a role, or at least was an important factor in spread of the insect. The recent discovery of this federally regulated invasive forest pest in a new region further underscores the importance of knowing how forest pests, human behavior, and firewood interact, and our lack of this knowledge represents a significant gap in the literature.

Over half of the selected articles were conducted between 2009 and 2014 (Fig. 1). Since 2014, a decreasing trend has emerged regarding the number of articles published, which could lead funding agencies, the scientific community, and general public to believe that the dispersal of forest insect pests through firewood is no longer an issue, or is not an important issue, neither of which is accurate (Seebens et al. 2017). While we have identified relevant information from the available literature, there is still much to be learned about insects, firewood, and potential pest movement.

Finally, only Jacobi et al. (2012) examined retail firewood, demonstrating that this significant source for acquiring firewood is understudied (the other articles examined firewood split or collected for the study, firewood that was confiscated, or firewood brought by campers). Much firewood is produced and sold by smaller businesses, and tracking where it was sourced, sold, and used is difficult and time consuming. Providing free or lower-cost firewood at campgrounds may be an alternative for reducing firewood transport by the public, although more research is needed on the economic costs and benefits of this alternative.

Conclusions

The literature identified in this scoping review examines insect incidence in firewood (showing that firewood serves as a vector for forest insect dispersal), assesses the effectiveness of heat treatments for firewood, and addresses human behavior and decision-making related to recreational firewood transport to analyze the rationale behind this behavior. These articles provide useful information to gain a better understanding of this issue and serve as a baseline for future research. Future research should explore the gaps identified in this scoping review to identify and obtain new information that will guide effective management. These gaps include: 1) policy and management assessment, 2) behavior and rule compliance assessment, 3) public awareness, 4) study of species less present in the literature, and 5) study of midwest and western regions of the United States, western Canada, and Mexico. Although research in the fourth and fifth gaps would give us more information on aspects we do not know, the most impactful research would fill the first through third gap. This research could potentially answer key questions such as why do people move firewood? Are messages being communicated effectively? What are the inconsistencies among regulations? Tangible benefits from new management strategies could include reduced impacts on forest health and ecosystem services, as well as a decrease in economic costs (e.g., management) associated with forest pest eradication or management and prevention of economic losses (e.g., timber industry).

The articles in theme 1, which addressed insect incidence in firewood, suggest that insects can emerge many years after trees are dead and a substantial amount of transported firewood has evidence of insect infestation. This supports the need for effective and consistent treatments and regulations, educational campaigns, and monitoring of firewood movement. Also, Jacobi et al. (2011; theme 3) found that only a third of the firewood assessed in a given National Park had been purchased inside the park, demonstrating the need to support efforts to increase local firewood sales, as firewood that is harvested and burned locally is not considered a threat for pest movement.

Invasive forest insects are a persistent problem worldwide and they have been introduced and spreading in North America since 1653 (Aukema 2010) and the acceleration of their spread across the continent through human-mediated pathways has been understood for over 100 yr (McManus and Csóka 2007). Further analysis of the human dimensions of forest insect pest dispersal through firewood movement is key for future invasive species management or, where feasible, eradication. Although the existing literature on this topic is limited, the articles addressing behavior and rule compliance (theme 5) suggest that firewood-related behaviors may be changed using informed approaches. Therefore, it is important to expand research that seeks to understand awareness and behaviors by the public in regard to firewood issues, and how professionals can better convey messages about the risks of moving firewood and the importance of obtaining firewood locally. Collaborating or co-managing with the public as a stakeholder by incentivizing education, accountability towards the resources (i.e., forests), and participation may make people more likely to change their firewood use behaviors (Decker and Chase 1997).

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