

Forest pests and wood pellets: A literature review of the opportunities and risks in the United States' northeastern forests

Alex Neidermeier^{a,*}, Cecilia Danks^a, Kimberly Coleman^b, Kimberly Wallin^c

^a The University of Vermont, Rubenstein School of Environment and Natural Resources, Burlington, VT, United States

^b SUNY Plattsburgh, Center for Earth and Environmental Science, Plattsburgh, VT, United States

^c College of Science and Mathematics, North Dakota State University, Fargo, ND, United States



ARTICLE INFO

Keywords:

Phytosanitation
Forest health
Wood pellets
Biomass supply chain

ABSTRACT

As interest in alternatives to fossil fuels increases, low quality timber may become more attractive as feedstock material for biomass energy. This low-quality timber, referred to here as salvage wood, can be used to manufacture wood pellets, a densified biomass energy product which can be used for electricity and heating. The process of converting wood to pellets also results in total pest mortality in the final product, an important consideration given wood pellet's international market and global concerns about phytosanitation, or the risk of pest spread. However, there is still potential to spread pests in the wood pellet supply chain. To better understand the potential benefits for forest health and the phytosanitary risks of the use of salvaged wood in the wood pellet supply chain, our study systematically reviews the literature published between 2000 and 2018, gleaned applicable considerations for the northeastern United States (US), a region already affected by the highest density of damaging forest pests in the country and an up-tick in wood pellet use. Our review focuses on three pest species likely to incur considerable change in northeastern US forests: emerald ash borer (*Agrilus planipennis* or EAB; an exotic, invasive species), hemlock woolly adelgid (*Adelges tsugae* Annand, or HWA; an exotic, invasive species), and southern pine beetle (*Dendroctonus frontalis* Zimmermann, or SPB, a native species). Our review finds that wood pellets are being recognized as phytosanitary in their final form and that the forest health opportunities for the use of salvaged wood exist are beginning to be acknowledged in the region. However, our results also indicate that the spread of pests is still possible in the feedstock pre-treatment supply chain, which have yet to be directly addressed in US-related scientific literature. Our review concludes that further research and action on the phytosanitary risks in the supply chain focus on individual pest species behavior during harvesting, on-site comminution of feedstock material, and local processing at facilities within USDA APHIS (United States Department of Agriculture Animal and Plant Health Inspection Service) quarantine zones for maximum mitigation. The results of these considerations can accrue benefits for forest health, mitigate the spread of forest pests, and support the use of an alternative energy to fossil fuels in a changing climate.

1. Introduction

Wood based biofuels offer potential for new opportunities and challenges at the intersection of alternatives to fossil fuel energy (Walker et al., 2013) and incentives for forest health management. Overall biofuel contributions in solid (such as firewood), liquid (such as ethanol), and gas (such as biogas from organic matter) forms are anticipated by Guo et al. (2015) to reach 30% of global energy demands by 2050. Degraded, low-value wood, which can be found after disturbances such as storms, drought, and insect infestations (Lamers et al., 2013) typically has a limited market in comparison to higher quality wood but may become more attractive as a feedstock material

for biomass energy (Levesque and Kingsley, 2017). Referred to as salvaged wood for the purposes of our review, it can be used for the manufacture of wood pellets, a densified product which can be composed of several types of organic matter (including various forms of wood), which can be used for heating and electricity (Thrän et al., 2017). One of a suite of biofuel products gaining interest in domestic and international energy and heating markets, global wood pellet production is estimated to have increased four-fold, from approximately six megatons to 26 megatons, between 2005 and 2015 (Thrän et al., 2017). These trends are also apparent in the northeastern United States (US), where in 2014 the US Energy Information Administration found a notable increase in the use of wood as a residential heating

* Corresponding author at: 2920 Georgia Ave. NW Unit 301, Washington, DC 20001, United States.

E-mail address: anneiderm@gmail.com (A. Neidermeier).

<https://doi.org/10.1016/j.foreco.2020.118415>

Received 4 March 2020; Received in revised form 20 May 2020; Accepted 3 July 2020

0378-1127/ © 2020 Elsevier B.V. All rights reserved.

source (EIA, 2018).

The increased interest in wood pellets globally can also be attributed to several advantages of wood pellets as an energy option, especially when compared to other forms of solid biofuel that can be used to produce heat and/or electricity like firewood or fuel chips. Fuel pellets, including those using fibrous materials other than wood, have an increased energy output per unit volume in comparison to other solid biofuel materials (Thr  n et al., 2017). These benefits both increase the potential profitability of pellets and an improvement on their transportability for domestic and international trade (Spelter and Toth, 2009). Pellets may also be an attractive option for residential heating systems that are transitioning from oil heat (Wood and Pellet, 2018). Although almost all wood pellets consumed domestically in the US are used for residential heating, the majority of US wood pellets (63% as of 2015) are exported to international markets (Thr  n et al., 2017). Internationally, wood pellets are more frequently used for electricity production, in which the pellets are typically co-fired with coal. This is most commonly practiced in Europe, although Canada has seen former coal plants, such as Atikokan in Ontario, transition completely to wood pellets for electricity production (Thr  n et al., 2017).

In addition to wood pellets' increased energy density, value per volume, and transportability in their final form (Thr  n et al., 2017), their use is creating new markets for degraded, low-value wood and timber (Levesque and Kingsley, 2017). In some scenarios, the use and sale of salvaged wood can create co-benefits such as keeping energy markets local (Buchholz et al., 2019) or supporting forest management goals after an ecological disturbance (Dale et al., 2015). Forest management goals can be met by silvicultural treatments aimed at dually supporting forest health, managing pest populations, and providing an economic incentive for forest management (Dale et al., 2015). The treatments can be preventive in nature (i.e. treatment or removal before an anticipated pest disturbance, such as a bark beetle outbreak) or a form of direct control (i.e. the removal after a pest disturbance has begun) (Dale et al., 2015).

In spite of these advantages, the use of salvage wood presents several challenges for forest managers and wood pellet facilities. Environmentally, research has indicated that the effects of extensive removal of forest residues, such as wood infested by pests, can have deleterious effects upon forest ecosystems (Foster and Orwig, 2006). Several studies have considered the risks of soil compaction from large machinery, disrupted geochemical cycles, and decreased biodiversity associated with the use of salvaged wood (Dale et al., 2015; Spelter and Toth, 2009). Beyond environmental concerns, dependence on an inherently sporadic feedstock spread across vast, remote, and challenging landscapes can compromise profitability. These economic challenges have been considered in several studies, especially in Canada where mountain pine beetle is a regular cause of forest disturbance (Foster and Orwig, 2006; Egnell et al., 2016; Barrette et al., 2015). Part of this economic challenge stems from the difficulty and expense of utilizing mobile or roadside chippers (Whalley et al., 2017). Concerns have also been raised about the potentially deleterious effects of low-grade, salvaged feedstock on wood pellet composition and quality (standardized according to regulations laid out by the Pellet Fuels Institute) and increased costs associated with processing lower-grade material with variable density and moisture (Lamers et al., 2013; Barrette et al., 2017).

These disadvantages, such as profitability and environmental impact, likely account for the relatively small portion of most companies' biomass feedstock composed of diseased and salvaged wood. Drax, for example, a U.K.-based energy company with pellet production operations in Mississippi and Georgia, reported that only 0.6% of their feedstock mix was procured specifically from diseased and damaged wood in 2017 (Graphics, 2018). Similar to other pellet mills in the US (Levesque and Kingsley, 2017), sawmill residues accounted for the largest percentage of Drax's feedstock mix at 40%, followed by low grade roundwood at 24%, thinnings at 18%, and branches, tops and

bark at 17% (Graphics, 2018).

Salvaged or not, one important advantage of wood pellets over other forms of solid biofuels is that the process of converting wood to pellets results in total pest mortality in the final product (Kopinga et al., 2010), an important consideration given wood pellet's international market and global concerns about phytosanitation, or the risk of pest spread (Kopinga et al., 2010).

Our study focuses on the intersection of forest health, phytosanitary risk mitigation, and wood pellets. To better understand the potential benefits for forest health and the phytosanitary risks of the use of salvaged wood in the wood pellet supply chain, we carried out a systematic review of the literature published between 2000 and 2018, gleanable applicable considerations for the northeastern United States (US), a region already affected by the highest density of damaging forest pests in the country (Stennes et al., 2010; Whalley et al., 2017) and an up-tick in wood pellet use (US Energy Information Administration, 2014). Our review focuses on three pest species likely to incur considerable change in northeastern US forests: emerald ash borer (*Agrilus planipennis* or EAB; an exotic, invasive species), hemlock woolly adelgid (*Adelges tsugae* Annand, or HWA; an exotic, invasive species), and southern pine beetle (*Dendroctonus frontalis* Zimmermann, or SPB, a native species). By extracting and analyzing themes from this body of literature, we identify areas for further research to support the integration of salvaged wood as a wood pellet feedstock with appropriate phytosanitary guidelines, to support forest health, fossil fuel alternatives, and risk mitigation.

2. Aim and scope

Our study is focused on assessing the literature relevant to the potential benefits and risks of using wood at risk of pest contamination (i.e. phytosanitary risk) as wood pellet feedstock and extracting themes from the resulting literature. We conducted a systematic review of the literature published between 2000 and 2018 that addresses the potential for forest pest management through wood pellet production, the risk for pest dispersal in the supply chain, and the key challenges and gaps identified in the literature. We review strategies from the literature for the use of salvaged wood resulting from silvicultural activities and the mitigation of phytosanitary risk along the wood pellet feedstock supply chain. By coding the resulting literature database based on emergent themes (such as economics and climate change), we summarize the current state of the literature on the subject, identify areas of further research, and orient the findings towards the case of the northeastern US.

In the context of this review, "pest" relates to insects, both native and exotic, in forested landscapes that alter or degrade ecosystem functions or services deemed valuable to humans. Local and regional scales of movement in the northeastern US (referring to the following states for this review: Vermont, New Hampshire, Maine, New York, New Jersey, Massachusetts, Rhode Island, Connecticut, and Pennsylvania) are considered. An emphasis is placed on three specific pests—emerald ash borer (*Agrilus planipennis* or EAB; an exotic, invasive species), hemlock woolly adelgid (*Adelges tsugae* Annand, or HWA; an exotic, invasive species), and southern pine beetle (*Dendroctonus frontalis* Zimmermann, or SPB, a native species)—anticipated to affect forested land in the region in the context of a changing climate. Non-forest-based feedstock (such as switchgrass), plantation-based feedstock (such as eucalyptus), and non-forest pests fall outside the scope of our study.

3. Background

3.1. Wood pelletization

The pelletization process creates a standardized product with an increased energy content per unit volume in comparison to firewood

and wood chips. Pellets are fabricated from a range of woody materials, including round and salvaged wood as well as residual sawdust and shavings (Lamers et al., 2013; Barrette et al., 2017). Differences in initial feedstock composition and quality can affect the treatment of these materials in the wood pellet supply chain. In general, however, feedstock is subject to debarkation, chipping, drying, and compaction to conform wood to a uniform size, energy density, and moisture content (Maciejewska et al., 2006). Processing intensity is dependent on the feedstock condition, with round wood being the most difficult to process and residues being the least difficult (Spelter and Toth, 2009). Moisture content and ash levels figure prominently in pellet processing and quality. Material in which bark is still present is first debarked to standardize the ash content in the final product (Brashaw et al., 2012) and chipped as appropriate to 70 mm prior to entering dryers (Maciejewska et al., 2006). All particles must then be brought to an appropriate moisture content of 12–17% of weight by volume as required by pellet presses (Maciejewska et al., 2006). The heat generated by the pressure of extrusion heats the lignin in the wood allowing it to act as binder for the product (Guo et al., 2015). The particles may also be steam conditioned to improve material binding, then pressed, extruded, cut to size, and hardened through cooling (Spelter and Toth, 2009).

Torrefaction is an additional processing option in which the initial feedstock is heat-treated to between 200 and 300 °C for 120 min with no oxygen, further reducing moisture content, decreasing the weight by volume, and increasing the energy content of the product (van der Stelt et al., 2011). Torrefied pellets can have an almost doubled increase in energy density (Thrän et al., 2017), increasing their value and ease of transport.

3.2. Forest pests

Insects contribute to many vital ecosystem services such as decomposition and nutrient cycling (Dajoz, 2000; Schowalter et al., 2018), pollination services for up to 90% of plant species (Klein et al., 2007), and indigenous biological control services (Losey and Vaughan, 2006). The negative impacts of forest pests, however, are felt across sectors worldwide, especially in temperate North America where Dale et al. calculated that pest disturbance exceeds forest fire disturbance by 50 to 1 in terms of acreage as of 2001 (Dale et al., 2001). Northeastern forests, especially those in New York, Pennsylvania, and Connecticut, have the highest number of species of damaging forest pests in comparison to other parts of the US. In these states, more than 45 pest species were found in several counties in 2013 (Liebhold et al., 2013). Humans are facilitating the movement of pests, largely through trade and a globalized economy (Everett, 2000; Levine and D'Antonio, 2003). Some of these pest species are indigenous to the ecosystems in which they are found but experiencing a shift in their native range in a changing climate, such as the southern pine beetle (*Dendroctonus frontalis* Zimmermann; SPB) (Clarke and Nowak, 2009). Others are exotic invasive species, such as the hemlock woolly adelgid (*Adelges tsugae* Annand; HWA) and emerald ash borer (*Agrilus planipennis*; EAB), which benefit from a lack of host resistance and natural enemies in their new habitats (Waring and O'Hara, 2005).

These three pests, EAB, HWA, and SPB, present significant economic and ecological changes to many forests in the northeastern US (Table 1). EAB, first found in Michigan in the 1990s, poses a serious threat to eastern forests due to the susceptibility of ash trees (*Fraxinus* spp.) to attack, the difficulty of early detection, and the prevalence of ash trees throughout the eastern US (Flower et al., 2013; Haack et al., 2015). Hemlock trees (*Tsuga canadensis*) similarly face a daunting future due to HWA, introduced to the eastern US from Japan (Havill and Montgomery, 2008). HWA in the east lacks natural enemies with eastern hemlock trees demonstrating a seeming lack of resistance to HWA feeding. Occupying a critical role as a keystone species, the demise of the hemlock is expected to incur changes in eastern ecosystems

(Havill et al., 2014).

The SPB differs from EAB and HWA as a species that is native to the southeastern US. SPB is currently part of regular disturbance regimes of southeastern forests where it affects several species of pine, including some of high commercial value such as the loblolly pine. By changing environmental conditions such as temperature and precipitation that impact tree health, a changing climate will impact the severity and duration of outbreaks while also changing pest ranges into more northeastern forests (Dodds et al., 2018; Gan, 2004).

3.3. Future outlooks for pests in the northeastern US

Pests were predicted by Lovett et al. in 2006 to be the primary driver of changes in species compositions in future decades in the northeastern US (Lovett et al., 2006). In addition to the risks of exotic invasive species spread inherent in an increasingly globalized economy (Lovett et al., 2016; Everett, 2000), a combination of warmer winters, changes in precipitation, and habitat destruction provide ample opportunity for human-assisted pest dispersal as well as shifting and expanding ranges (Dukes et al., 2009; Fitzpatrick et al., 2012; Hlásny and Turčáni, 2009; Logan et al., 2003; Lovett et al., 2006). Insects are also likely to benefit under a warming climate scenario as temperature is a crucial component of insect development (Hlásny and Turčáni, 2009; Weed et al., 2013). Extension of growing seasons by 4–6 weeks, as predicted by Hayhoe et al. (2007), will affect emergence and voltinism (or, number of generations per season) of many insect species as well as their associated host species, predators, and pathogens (Dukes et al., 2009; Weed et al., 2013).

4. Methods

For our study, we conducted a systematic literature review on the phytosanitary risks and opportunities in the wood pellet feedstock supply chain. Following methods similar to those laid out by Pickering and Byrne for a systematic quantitative literature review (Moher et al., 2009; Pickering and Byrne, 2014), the research topic was used to identify keywords as found in Table 2. We then used these keywords to conduct a search across five research databases (Science Direct, Web of Science, EBSCO Host Environment Complete, ProQuest Agricultural and Environmental Science Database, and Google Scholar), which resulted in a total of 261 papers once duplicates were removed, as can be seen in Fig. 1. Searches within all databases included the title, body, and works cited of papers. Each search consisted of a search phrase composed of a term from each of the columns in Table 2 (organized broadly by the parameters of ecosystem, material, action, and risk subject), until all possible permutations were exhausted. This included plurals and alternative word endings (i.e. phytosanitary and phytosanitation) as relevant. We generated a database of results based on a protocol developed for the inclusion and exclusion of papers to the study (Pickering and Byrne, 2014; Pullin and Stewart, 2006) which totaled 196 papers. Papers were only included in the database that were published between 2000 and 2018, in English. Papers were included regardless of geographic focus. We excluded papers that focused on a non-forest-based feedstock (such as switchgrass), a plantation-based feedstock (such as eucalyptus), or a non-forest pest in order to focus on pest species specifically affecting natural forest ecosystems which may be providing feedstock for the wood pellet industry.

We excluded papers that focused on a non-forest-based feedstock (such as switchgrass), a plantation-based feedstock (such as eucalyptus), or a non-forest pest in order to focus on pest species specifically affecting natural forest ecosystems which may be providing feedstock for the wood pellet industry. This resulted in a total of 142 papers that were saved in the reference management software, Zotero.

We conducted a qualitative analysis of the papers in our database using NVivo 12 software, a research software commonly used by social scientists to conduct qualitative and mixed methods work. NVivo allows

Table 1
Overview of the three forest pest species covered in this review posing risks to northeastern US forests.



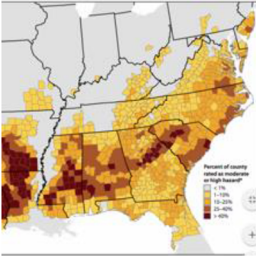
Pest name & risk maps for the Eastern US	Relevant Pest Characteristics
Emerald Ash Borer (Forest, 2019) <i>Agrilus planipennis</i> 	Pest description: Exotic invasive insect (Haack et al., 2015) Tree species at Risk: Ash trees (<i>Fraxinus</i> spp.) Breeding Material: Adults feed on foliage. Larval instars feed on outer and inner bark (phloem), outer sapwood (Wei et al., 2007) Damage: Galleries created in the tree cambial region resulting in crown dieback and eventual tree death (Haack et al., 2015) Relevant breeding characteristics: Locates trees through visual (purple and green) and olfactory indicators from bark and foliage. Flight period at peak in June and July in northern US (Haack, et al., 2002) Dispersal characteristics: Natural dispersal of several kilometers per season through adult flight. Likely imported to the US through wood packaging materials such as pallets. Firewood also a likely pathway for regional dispersal. Adults can be transported by humans and vehicles long-distances (Haack et al., 2015).
Hemlock Woolly Adelgid ¹ <i>Adelges tsugae</i> Annand 	Pest description: Exotic invasive insect (Parker et al., 1998, 1999; Skinner et al., 2003) Tree species at Risk: Eastern and Carolina Hemlock (<i>Tsuga canadensis</i> and <i>Tsuga caroliniana</i>) Breeding Material: Areas of new growth on branches Damage: Needle drop, restricted nutrients to tree. Tree mortality can occur within 5–10 years. Relevant breeding characteristics: Two generations per year. HWA reproduction is parthenogenetic (asexual) in North America. Eggs are laid in web-like, viscid ovisacs secreted by adult HWA. Dispersal characteristics: HWA's northern range is limited by cold temperatures. It has been dispersed by wildlife, imported trees, humans, and hurricanes. It is especially susceptible to spread during period of ovisac presence (white, clinging sacks) on trees.
Southern Pine Beetle ⁹ <i>Dendroctonus frontalis</i> Zimmermann 	Pest description: Native to southeastern US Tree species at Risk: All pine species including pitch pine (<i>Pinus rigida</i> .), loblolly (<i>Pinus taeda</i>), red pine (<i>Pinus resinosa</i> Ait.), Scots pine (<i>Pinus sylvestris</i> L.), eastern white pine (<i>Pinus strobus</i> L.). Adjacent trees such as hemlock may also be susceptible to attack (Dodds et al., 2018). Breeding Material: Inner and outer tree bark. Damage: Tree girdling and water blockage by associated fungi resulting in tree death (Clarke and Nowak, 2009). Relevant breeding characteristics: Multiple generations per season possible (up to nine in the southern states) in favorable conditions. Aggregation pheromones initially released by females, then by attracted males after arrival. Dispersal characteristics: Infestations have spread as quickly as 120 ft/day (Clarke and Nowak, 2009). Beetles may continue development during winter months (although consistent freezing temperatures may impact population sizes). Adults are capable of flying up to two miles (Turchin and Thoeny, 1993).

Table 2
Search terms for literature analyses.

Ecosystem	Material	Action	Risk subject
Forest	Forest fuel(s)	Phytosanita*	Invasive species
	Wood pellet(s)	Life cycle analysis	Invasive insect(s)
	Salvage(d) wood	Supply chain risk assessment	Forest pest(s)
	Bioenergy		
	Biomass		

researchers to identify themes, as well as linkages and patterns between themes, in qualitative data, such as text, video, audio, and imagery. It is well suited to analyzing text and was thus appropriate to use for our review. To complete this analysis, we carried out an initial assessment of the database and organized it using a set of four *a priori* codes (Glesne and Peshkin, 1992) based on the literature described in the introduction of this paper. The *a priori* codes were based on the Action, Material, and Risk Subject categories used in the search term organization in Table 2. As seen in the Venn diagram in Fig. 2, the *a priori* codes were created at the overlap of these categories, namely: Action, Material (AM); Action, Risk Subject (AR); Material, Risk Subject (MR); and Action, Material, Risk Subject (AMR). At this point, literature that only pertained to one component, i.e. a paper that discussed only a search term in the “Material” category in Table 2 but not an “Action” or “Risk subject” term, were deemed ineligible and removed, resulting in a final database count of 142 papers. Using these 142 papers and four *a priori* codes, we

conducted a qualitative analysis on the papers using nVivo 12, a software program that facilitates qualitative analysis of text and other media.

We developed operational questions to apply to the papers as seen in Table 3 for each of the four aforementioned *a priori* codes. These were developed iteratively around themes that arose while reviewing the literature (Moher et al., 2009; Pickering and Byrne, 2014). “Action, Risk Subject” papers (AR), for example, considered interactions between silvicultural techniques and management of forest pests (including but not limited to EAB, HWA, and SPB). “Material, Risk Subject” papers (MR) considered the effect of forest pests on wood pellet feedstock quality. Papers categorized as “Action, Material” (AM), broadly considered the effectiveness of pelletization on phytosanitation (i.e., the interaction of wood pellets and phytosanitation). The papers most relevant to this analysis were those coded at the “AMR” node, which considered the various intersections of wood pellets, phytosanitation, and forest pests.

Papers were not coded exclusively within single categories (i.e., a paper could address both an “Action, Material” code and an “Action, Material, Risk Subject” code) as different section of papers sometimes offered information on more than one of the questions associated with the *a priori* codes. For example, a section of a paper’s text could be relevant to impacts of feedstock quality on pellets (“Material, Risk Subject”—MR) while another section in the same paper discussed the effects of pelletization on phytosanitation (“Action, Material”—AM). Analysis of results produced in nVivo was carried out in Microsoft Excel v15.34.

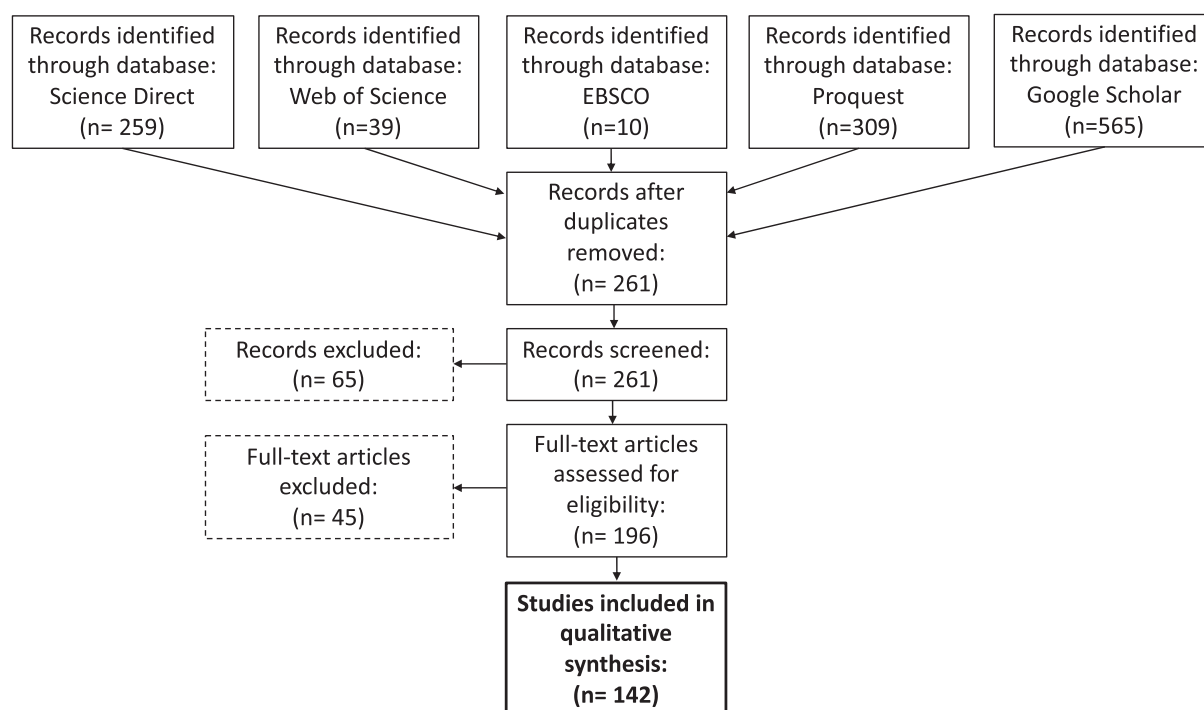


Fig. 1. PRISMA diagram outlining the order of operations for completing the literature review systematically.

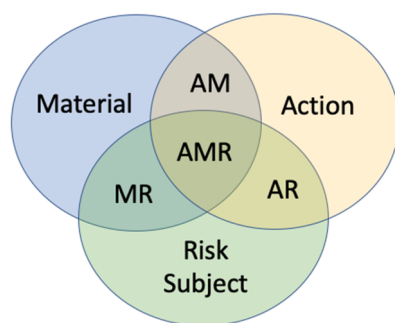


Fig. 2. Venn diagram of *a priori* coding categories (from Table 3) used for literature analysis. “AM” refers to the “Action, Material” category, “MR” to “Material, Risk Subject,” “AR” to “Action, Risk Subject,” and “AMR” to “Action, Material, Risk Subject”.

5. Results

5.1. Results overview

Based on the coding analysis of the 142 papers in the database, we were able to understand themes within the literature. These papers came from several journals (Fig. 3) the majority of which were published by the journal Biomass and Bioenergy, followed by Forest Ecology and Management, and Biological Invasions. They also ranged in geographic coverage with 33 of the papers being specifically internationally focused, mostly related to phytosanitation practices in Europe. Papers from Canada were also prevalent, addressing the economics, logistics, and potential of using wood salvaged from mountain pine beetle events for the wood pellet industry. Twelve papers focused explicitly on the US, with most focusing in some capacity on the growing wood pellet industry in the Southeast. The remaining papers did not have a specific geographic focus or were focused on global issues.

To compare paper outcomes as coded using the themes outlined in Table 3, the number of papers for each category (AM, AR, & MR, and

AMR) was first extracted (i.e. 4 total papers in the MR category). The sum total (including duplicates between categories) was then divided by each individual category’s number of papers to calculate the categories’ percentages Fig. 4. Following this method, the largest percentage of papers (39%) fell in the “Action, Material” category, which broadly considered the effectiveness of pelletization on phytosanitation. “Action, Risk Subject” papers, focusing on silviculture strategies for forest pest mitigation, comprised 28% of the database while “Material, Risk Subject,” concerning the effect of pests on feedstock quality, accounted for only 2% of papers. “Action, Material, Risk Subject” papers, most relevant comprehensively to this literature review, encompassed 28% of the literature. The results for each category are described thematically in the sections below.

5.2. Action, Risk Subject (AR) category: Silviculture and pest management

Twenty-eight percent of the analyzed papers were coded in the “Action, Risk Subject” category. These papers placed value on specific types of direct pest control (such as thinning, pre-salvage, etc.) and indirect control (such as prescribed fire, biological control, and the use of pest-attracting pheromones), but did not necessarily link these subjects to bioenergy or wood fuels. Papers discussing specific tactics for managing pests also generally fell in this category, with 13 papers considering EAB management strategies, ten considering HWA, and two considering SPB.

Collectively, papers in this category indicated that management decisions about forests pests are based on the long-term goals for the area (Dale et al., 2017b; Dale et al., 2017a), the characteristics and biology of the pest, and the level or intensity of invasion or spread (Muzika, 2017; Waring and O’Hara, 2005). Silvicultural practices can change the successional dynamics of a forest affected by pests through the removal or preservation of affected tree species (Dale et al., 2017b; Dale et al., 2017a). We found limited research about the efficacy of prescribed silviculture methods for long-term forest health to manage specific pests (Dale et al., 2015; Muzika and Liebhold, 2000). Short-term studies have examined preventive pest management (the removal of wood that is expected to become infected) and direct control (the

Table 3

Coding structure used for literature analysis with the number of paper results by category of code.

Code	Coding hierarchy	Coding description (operational questions)	Number of Papers
AM	Action material		85
AM1	Action material\Biofuel becoming invasive	Does the paper examine a bioenergy crop becoming invasive?	9
AM2	Action material\Biomass extraction best practices	Does the paper consider best practices for biomass extraction?	7
AM3	Action material\Forest management + economics	Does the paper link the wood pellet industry to forest management?	16
AM4	Action material\Pest management + climate change	Does the paper consider pest management as a method to manage forests as a climate change adaptation strategy?	15
AM5	Action material\Phytosanitation of wood	Does the paper examine phytosanitation for products unrelated bioenergy?	25
AM6	Action material\Wood pellets + forest management	Does the paper link the wood pellet industry to forest management?	23
AR	Action Risk Subject		61
AR1	Action Risk Subject\Direct control	Does the paper place value on direct control (including preventive removal, pre-salvage, and thinning) to reduce pests?	24
AR2	Action Risk Subject\EAB human movement	Does the paper consider the mechanisms by which humans could facilitate the movement of EAB?	5
AR3	Action Risk Subject\EAB management	Does the paper consider forest management techniques for EAB?	13
AR4	Action Risk Subject\HWA human movement	Does the paper consider the mechanisms by which humans could facilitate the movement of HWA?	1
AR5	Action Risk Subject\HWA Mgmt.	Does the paper discuss the management of HWA?	6
AR6	Action Risk Subject\Indirect control	Does the paper place value on indirect control (including prescribed fire, semiochemical (pheromone) attractors, and biological control) to reduce pests?	10
AR7	Action Risk Subject\Pest management, nonspecific	Does the paper evaluate management for pest risk generally, not related to specific pests?	8
AR8	Action Risk Subject\Silvicultural best practices + pests	Does the paper consider silvicultural best practices for forest pests without specific reference to EAB/ HWA/ SPB?	27
AR9	Action Risk Subject\SPB management	Does the paper consider forest management techniques for SPB?	2
AR10	Action Risk Subject\SPB human movement	Does the paper consider the mechanisms by which humans could facilitate the movement of SPB?	0
MR	Material Risk Subject		4
MR1	Material Risk Subject\Insects as a source of biofuel	Does the paper consider insects as a source of biofuel?	1
MR2	Material Risk Subject\Pest + Feedstock Quality	Does the paper consider the effect of pests on feedstock quality?	3
MR3	Material Risk Subject\Pest + Feedstock Quality\Salvage negative effect on pellet quality	Does the paper suggest a negative effect on pellet quality when pellets are made from salvage wood?	1
AMR	Action Material Risk Subject		69
AMR1	Material Risk Subject Action\positive economic, fuel from infected wood	Does the paper suggest economic benefits from using infected wood as a fuel source?	35
AMR2	Material Risk Subject Action\negative economic, fuel from infected wood	Does the paper suggest that infected wood is an economically unviable source for fuel?	11
AMR3	Material Risk Subject Action\Phytosanitation + bioenergy feedstock	Does the paper evaluate phytosanitation risks in non-wood bioenergy feedstocks?	13
AMR4	Material Risk Subject Action\Wood fuel, supply chain, & phytosanitation	Does the paper consider the phytosanitary risks in the wood fuel supply chain?	22
AMR5	Material Risk Subject Action\Policy + phytosanitation + wood fuel supply chain	Does the paper reference policy that considers phytosanitation in the wood fuel supply chain?	5
AMR6	Material Risk Subject Action\Chipping insufficient	Does the paper find chipping alone to be insufficient for pest mortality?	13
AMR7	Material Risk Subject Action\On-site comminution recommended	Does the paper recommend that comminution take place on-site to avoid phytosanitary issues in the wood fuel supply chain?	3
AMR8	Material Risk Subject Action\Pellets, management, phytosanitation	Does the paper consider wood pellets a phytosanitary product resulting from the management of forests?	4
AMR9	Material Risk Subject Action\Pellets + phytosanitation	Does the paper place value on pelletization for phytosanitation?	8
AMR10	Material Risk Subject Action\Climate, NE, pellets, management, phytosanitation	Does the paper consider wood pellets or forest fuels more generally, forest management, and phytosanitation in the context of a changing climate in the northeast?	1

**Fig. 3.** Percentage of papers in final database by publishing journal. Only journals contributing at least three papers are included in this figure.

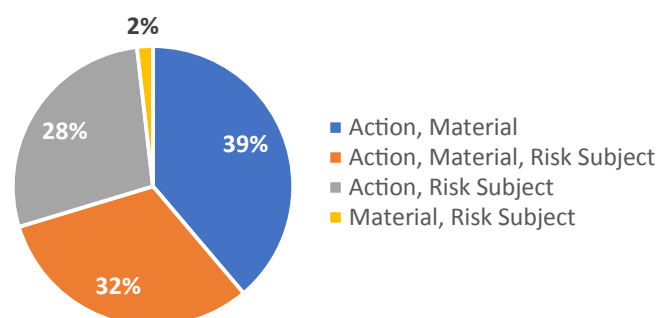


Fig. 4. Percentage of papers that fell into the four coding categories (from codes in Table 3).

removal of trees already dead or suspected to be infested) that have been shown to be effective techniques against outbreaks such as that of the mountain pine beetle in Canada (Safranyik and Wilson, 2006). Other methods, such as thinning and prescribed fire, share the goal of improving the health of a stand and thus increasing overall resiliency to pests (Waring and O'Hara, 2005). These tactics may be used in combination with pheromone-based attractants (i.e., mountain pine beetle) (Evenden and Silk, 2016) or biological control (i.e. HWA) (Vose et al., 2013). The level of infestation can dictate the management strategy (Muzika, 2017).

The literature indicated that knowledge of the life cycles of pests is key in determining the best strategy for management (Table 4). Removal of trees infested with SPB in the summer, for example, may limit an on-going infestation. However, winter removal may be more effective by exposing immature SPB's to decreased temperatures, increasing mortality (Dodds et al., 2018; Gan, 2004).

Our results indicate that the efficacy of managing EAB, HWA, and SPB for forest health varied across studies. Studies indicated that early silvicultural treatments to eradicate EAB failed and chemical treatments were not uniformly effective (Looney et al., 2015; McCullough et al., 2007). Pre-salvage and salvage operations were generally recommended for forest managers attempting to redeem value from dead or dying trees (McCullough and Poland, 2015). More options existed for the management of HWA, including leaving the stand untreated, thinning treatments, and harvesting and extracting most or all hemlocks in an area (Orwig and Kittredge, 2005). Selective cutting of overstory trees to expose lower branches to more sunlight was shown to aid in the mitigation of HWA populations (Brantley et al., 2017). Silvicultural techniques, including salvage harvests, were found to be effective in managing SPB (Belanger et al., 1993; Gan, 2004). Thinning was found to improve the ability of trees to resist SPB infestations and was thus considered an effective strategy to limit SPB population growth. A study from Clark and Nowak in 2009 noted that aerial views to define an SPB outbreak pattern. The invasion pattern could then be used to target felling of newly infested trees towards trees that had already been vacated by SPB to more effectively manage their populations (Clarke and Nowak, 2009).

Table 4

Gantt chart of months posing highest risk (in red) of EAB, HWA, and SPB transmission in the northeastern US, subject to alterations in a changing climate.

	J	F	M	A	M	J	J	A	S	O	N	D
Emerald Ash Borer (McCullough and Poland, 2015)												
Hemlock Woolly Adelgid (Parker et al., 1998; Skinner et al., 2003)												
Southern Pine Beetle (Clarke and Nowak, 2009)												

5.3. Material, Risk Subject Category: Effects of pests on feedstock quality

Only 2% of papers fell into the "Material, Risk Subject" category, which focused on the effect of pests on feedstock quality. Ash content was documented as an important component of ensuring standard quality of wood pellets that can be affected by the condition of the incoming feedstock (Looney et al., 2015; Levesque and Kingsley, 2017; Graphics, 2018). The findings indicate that although feedstock quality can be negatively affected by disease and pests, it is possible to use such wood to create wood pellets. For example, Qin et al. found that feedstock could be varied and improved to an acceptable level for pellet production by adding higher quality parent material to the mix (Qin et al., 2018). Similarly, Barrett et al. found in 2017 that trees affected by spruce budworm in Canada would still be eligible for use as a wood pellet feedstock (Barrette et al., 2017).

5.4. Action, Material category: Effectiveness of pelletization on phytosanitation

The largest share, 39%, of the 142 papers fell into the "Action, Material" category (Fig. 4). These papers considered, for example, best practices for biomass extraction (AM2), the potential for overlap between the wood pellet industry and forest management goals (AM3), and the phytosanitation of wood products (AM5). The literature indicated that phytosanitation standards varied between regions and countries and did not always meet treatment recommendations given in the emergent scientific literature (see Table 5). The relative effectiveness on pest death of chipping, grinding and heat treatments were generally dependent on the degree and length of treatment as well as life cycle and mortality factors of specific pests. No EAB, for example, remained at particle sizes of less than 2.5 cm. EAB was also eradicated after being heat-treated for 120 min at 60 °C (McCullough et al., 2007; McCullough and Poland, 2015). Thirteen papers were found in the literature that indicated that chipping alone may not be sufficient for phytosanitation. However, given the combination of chipping, grinding, compression, and heating described for the pelletization process, phytosanitation risks of wood pellets as a final product were found to be effectively eliminated (Batidzirai et al., 2014; Belanger et al., 1993; Kopinga et al., 2010; Safranyik and Wilson, 2006). Furthermore, in some literature focused on phytosanitary standards for international trade, wood pellets are placed in the same category as fiber board and pressed timber, which are assumed to pose no risk for pest transmission (USDA, 2014; EPPO, 2015). Table 5 compares several phytosanitary standards (domestic and international) to common wood fuel processing steps based on the review results, illustrating the ability of pelletization to effectively eliminate phytosanitary risks.

5.5. Action, Material, Risk Subject Category: Wood pellets, pests, and phytosanitation

5.5.1. Overview

Finally, 32% of the papers analyzed were coded for questions falling in the "Action, Material, Risk Subject" category (summarized in Fig. 5;

Table 5
Comparison of wood fuel phytosanitary standards to the phytosanitation created through the pelletization process.

Phytosanitation standards/recommendations		Aspects of pelletization that impact pest mortality	
		International	APHIS
Product size	Heat treatment	<ul style="list-style-type: none"> European Pellets Standard: 2.5 cm in any dimension and Less than 3% of chips > 16 mm (not to exceed 30 mm) (EPPO, 2015) Defined by NPPO (National Plant Protection Organization) of importing country (EPPO, 2015) 	<ul style="list-style-type: none"> For Insects: Product size < 2.5 cm (McCullough et al., 2007) For Bacteria, fungi, and viruses: Additional treatment needed (Koplinga et al., 2010) Dependent on particle size and pest Most pests: 70 °C for 1 h Virus: 74–80 °C for 1–4 h (Koplinga et al., 2010) At least less than 20%, but dependent on other factors (Koplinga et al., 2010) Aerobic composting of materials at temperatures of > 70 °C for several can eliminate pests including nematodes, bacteria, and fungi (Koplinga et al., 2010)
		<ul style="list-style-type: none"> Products must be less than 2.54 cm (USDA, 2014) Products must be heated to a minimum of 71.1 °C for 75 min (USDA, 2014) Chips must not contain any free water (USDA, 2014) Products must have documentation of pressure treatment if needed (USDA, 2014) < 15% with fungal fructification (USDA, 2014) Restrictions on chips from 60°E & tropic of Cancer (USDA, 2014) 	<ul style="list-style-type: none"> Final pellet size between 6.35 and 7.25 cm (Maciejewska et al., 2006) Torried products are treated to 120 min at 200–300 °C (Levesque and Kingsley, 2017; Koplinga et al., 2010) Non-torried pellets heated as necessary to achieve requisite moisture (Maciejewska et al., 2006) Dried to 12–17% humidity (Maciejewska et al., 2006) Bark removal (Brashaw et al., 2012) Pressed into extrudable form (Spelter and Toth, 2009) Final pellet product-no regulation needed by FAO (Food and Agriculture Organization (FAO), 2011)
Moisture requirements	Other treatments/restrictions		

full codes in Table 3). For papers with codes AMR1 and AMR2, in addition to addressing wood pellets, pests, and phytosanitation, economic benefits and risks of using wood salvaged from pest events for bioenergy were also considered, with 35 papers citing positive economic benefits and 11 identifying challenges (with some papers also citing both). These represented 39% of the combined AMR category literature. Codes AMR3, AMR4, AMR5 considered phytosanitary risks in bioenergy feedstocks and wood fuel supply chains, either by identifying tactics to manage specific risks or by analyzing policy to tackle those risks and represented 35% of the AMR literature. Thirteen papers found that chipping wood salvaged from pest and disease events may not be sufficient for pest mortality, especially for insects such as the EAB which are strong fliers and difficult to detect (Haack et al., 2015) (AMR6 comprising 11% of AMR literature). Three papers specifically recommended on-site comminution (processing that could include debarking, chipping, or other reductive action) to mitigate phytosanitary risks. Codes AMR8 and AMR9 (10% of the AMR category) identified papers that considered pellets as a phytosanitary final product resulting from the management of forests for pests or, at a minimum, placed value on the pelletization process for phytosanitation. Only one paper, which focused on just one pest species (SPB), considered wood pellets themselves as a phytosanitary final product in the context of forest pest management and a changing climate for the northeastern US (Dodds et al., 2018), indicating that the specific phytosanitary risks of diseased and infested wood in the pellet industry in this region have not been holistically evaluated.

5.5.2. Pest risks in pellet feedstock pre-treatment

Several themes arose from papers in AMR category in relation to phytosanitary risks in the wood fuel supply chain, including for the collection of wood pellet feedstock. Papers indicated that although pelletization is an effective means of addressing phytosanitary risks for the end product, the local transportation of feedstock materials from harvest to production site can still facilitate the spread of pests. Consideration of the sourcing, harvest procedures, on-site storage, on-site comminution, extraction, local transportation of feedstock, in addition to the potential for human error in even the most robust of systems, should be considered when handling potentially unsanitary wood. Notably, no papers were found which specifically examined the phytosanitary risks in the wood pellet supply chain in the US in our review. Furthermore, papers were not found which addressed the potential role of human error and compliance with sanitation rules and guidance.

5.5.2.1. Sourcing. The literature indicated that the distance of processing facilities to feedstock sources was an important consideration for a wood pellet enterprise's profitability as costs increase with transportation expenditures (Yemshanov et al., 2014). Given that pest-salvaged wood may be reclaimed from a single disturbance event, a feedstock source may be limited to a few years of opportunistic harvesting (Safranyik and Wilson, 2006). The proximity of feedstock to the perimeters of areas not known to be affected by pests should be factored into procurement and transportation logistics to decrease phytosanitary risks (Kühmaier et al., 2016; Koplinga et al., 2010).

5.5.2.2. Harvest. We found literature indicating that the timing of silvicultural interventions is critical to managing phytosanitary risks in the feedstock supply chain. The Gantt diagram in Table 4 details estimated risk periods for the three pest species of focus for our study, HWA, SPB, and EAB, as an example. During the months indicated in red, pests are at a higher risk for transmission to other local trees. For example, harvest of trees affected by EAB was recommended outside of the months of May to August (Haack et al., 2015). As ash trees also frequently sprout from the stumps, prevention of future colonization by EAB would require that stumps be cut to less than 2.5 cm or treated

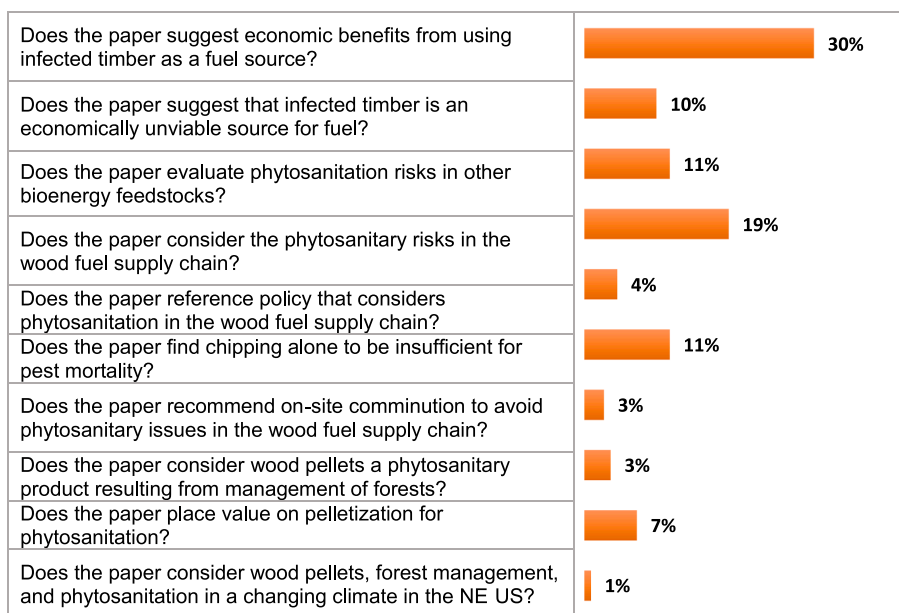


Fig. 5. Breakdown of literature falling in the “Action, Material, Risk Subject” category by the percentage of papers covered.

with an herbicide (Petrice and Haack, 2011). Similarly, for SPB, harvest ideally takes place after the flight period to effectively manage populations (Waring and O’Hara, 2005). Harvesting guidelines were also found to exist for the management of outbreaks based on specific invasion characteristics of SPB (Clarke and Nowak, 2009). For HWA, in spring and early summer, literature indicated that attention should be given to the accidental transportation of ovisacs (Vose et al., 2013) (Table 1), which may cling to equipment or handlers.

5.5.2.3. On-Site storage. As demonstrated in studies for several species of pest in Europe, stockpiling of forest fuels before treatment or transport may pose a phytosanitary risk (Lattimore et al., 2009; Schroeder, 2008). Studies from this region found that stockpiles harboring pests can act as an attractant for additional invasions (Victorsson and Jonsell, 2013), especially for pests such as the SPB, which release attractant pheromones (Clarke and Nowak, 2009). The risks associated with specific pests should be considered when designing a fuel wood terminal layout for the collection of feedstocks across regions (Kühmaier et al., 2016). Avoidance of flight periods of certain pests can mitigate their potential for spread to other parts of the forest (Waring and O’Hara, 2005). Care should be taken to avoid stockpiling at susceptible times and to avoid placing piles near the boundaries of known pest areas to decrease the risk of dissemination and establishment of pests into new regions.

5.5.2.4. On-site comminution. The processes of grinding, heating, chipping, and compression contribute to the management of phytosanitary risk. However, these actions are typically not applied until the biomass arrives at the processing facility. This is largely due to cost and limited availability of mobile chippers (Whalley et al., 2017), and logistical challenges in the movement of machinery within forested and remote areas. However, on-site comminution can be an extremely effective method for lowering the risk of pest spread. This is especially relevant in scenarios where the feedstock will be left at a holding site before transportation to a wood pellet mill (Kopinga et al., 2010). The efficacy of the comminution method on pest mitigation is species-dependent.

5.5.2.5. Extraction and local transportation. Care must be taken to ensure that “hitchhikers” are not accidentally spread by equipment. This caution is especially necessary for strong fliers such as EAB, which

were found to travel on vehicles long distances, further evidenced by EAB’s dispersal along main transportation routes (Haack et al., 2015). For transportation of biomass as whole logs, residues, or chips from a terminal to a processing facility, there is also a risk of losing infested wood in uncovered vehicles (Kopinga et al., 2010).

5.5.2.6. Wood pellet transportation. Once materials have been converted to wood pellets, there is effectively no risk of the spread of forest pests (Batidzirai et al., 2014; Safranyik and Wilson, 2006; USDA, 2014).

5.6. Discussion

Although wood pellets are themselves phytosanitary as a final product, risks still exist during the harvest and transportation of infested and low-grade wood. A number of articles in this review found that these risks are dependent on factors such as the timing of the harvest, the level of infestation, and the silvicultural method used, all of which are, in turn, dependent on a pest’s life cycle and behavior (Klein et al., 2007; Haack et al., 2015). These studies indicated that local comminution (such as chipping, grinding, etc.) can mitigate much of the phytosanitary risks associated with infected feedstocks. Our review also found evidence that although nematodes, fungi, and other pathogens may survive such on-site comminution, wood pelletization eliminates even these risks (Kopinga et al., 2010). Recommendations also emerged from the literature on the proximity of storage terminals to healthy trees if infested biomass is going to be accumulated at the forest level (Kühmaier et al., 2016; Kopinga et al., 2010). Studies indicated that on-site storage (in or near the harvest location) of infested materials may pose the largest risk in the feedstock supply chain, as infested debris piles could act as an attractant and pose a risk to nearby healthy trees (Kühmaier et al., 2016; Yemshanov et al., 2014). Our review, however, indicated that the ability of specific insects relevant to the northeastern US to establish in local storage and transportation scenarios is an area for further research which should prioritize insects posing the largest risk. Indeed, we focused on three macro species of forest pests, but further investigation of micro forest pests, such as rusts and fungi, to circulate in the pre-treatment supply chain should also be further evaluated. The results of such research could be instrumental in designing and locating pre-processing terminals and procedures to minimize phytosanitary risks (Kühmaier et al., 2016).

Our findings indicated that research is needed to support the use of

infested wood for the wood pellet industry while ensuring that phytosanitary standards are adequately supported, especially for the north-eastern US. Efficient phytosanitary compliance will require further research into the efficacy of silvicultural methods for specific pests (Tables 1, 4 and 5) and regional resources for management (Muzika, 2017; Safranyik and Wilson, 2006). Further research will also need to account for human error in the supply chain and other potentially deleterious effects on ecosystem (Foster and Orwig, 2006). The contribution of this feedstock to the wood pellet supply chain has not been assessed thoroughly in the US and is an area for further research. The economic and logistical challenges of connecting markets to accessible areas with pest-damaged wood to produce pellets was a theme identified in the literature (Nicholls et al., 2018). Studies of this nature were from places such as Canada, Russia, and Europe, for example (Goltsev et al., 2012; Stupak et al., 2007; Schroeder, 2008), but none were found which looked directly at the US. The literature suggests that economic incentives to utilize salvaged wood from pest events may be needed to offset the increased costs of transportation from harvest to facility (Barrette et al., 2017; Stupak et al., 2007). This could be partially supplemented by value-add processes such as torrefaction, which may increase profitability among other advantages (Batidzirai et al., 2014). However, the literature indicates that better connecting companies, energy facilities, and relevant community groups to help all parties be “nimble” as opportunities arise after an outbreak event may be beneficial. For example, a partnership was formed in Canada between the Pacific BioEnergy Corporation (a pellet mill), a local First Nations timber harvesting group, and Tolko Industries (a sawmill) to produce wood pellets from mountain pine beetle salvage, providing multiple benefits (Tolko, 2014). Application of our results suggests that in order to support such associations in managing phytosanitary risks associated with the pre-treatment supply chain, clear guidelines and policy should be developed on treatment of specific pests, especially in relation to quarantine zones (Table 4) (Allen et al., 2017; FAO, 2011), with the wood pellet market providing a possible incentive (Dodds et al., 2018; Dale et al., 2017a). Additionally, to ensure sustainable use of forest resources, policies, such as those found in Belgium and other EU countries requiring biomass feedstock to be sourced from sustainable forest management activities (Thrän et al., 2017), which also consider the ecological effects of biomass removal (Lamers et al., 2013; Egnell et al., 2016), should be developed for US use of wood pellets. Certain programs and credentials such as the Sustainable Forestry Initiative and the Forest Stewardship Council likely address these concerns but are, as yet, not federal policy.

In the future, northeastern forests are likely to face an increase in pest-damaged forest biomass as pest ranges shift in a changing climate (Dukes et al., 2009; Fitzpatrick et al., 2012; Weed et al., 2013) and the risk of introduction of new exotic invasive species rises (Lovett et al., 2016). This concern was evident in our review in the case of SPB, for example, which is being found in more northerly locations, including New Jersey, New York and Connecticut (Dodds et al., 2018; Gan, 2004), and is forecasted to expand as far as southeastern Canada in the coming decades (Lesk et al., 2017). Similarly, HWA, which is currently limited by colder winter temperatures in the north, is predicted to expand across the Northeast by the end of the century (Fitzpatrick et al., 2012; Paradis et al., 2008). In the context of an increasing globalized economy, a changing climate, new incentives for alternative energies, and an uptick in the use of biomass for energy in the US, we urge more investigation and action into the use of salvage wood from pest events for energy while maintaining cradle-to-grave phytosanitary standards. These phytosanitary calculations will also need to include the role of human error and compliance, even in robust systems. Effective measures will need to overcome perceptions of minimal risk and aversions to committing effort and funding to truly minimize risks, especially in light of the high cost of potential error. Connecting these factors can bring the northeast better managed forests, local economic incentives, and more options for alternative energies.

6. Conclusion

The use of low-grade wood salvaged from pest events and silvicultural treatments to manage pest populations presents an opportunity as a bioenergy feedstock source. The use of wood pellets has increased globally, likely due to their increased value (as compared to wood chips for example), energy per volume, transportability, and elimination of phytosanitary risk. However, beyond wood pellet's phytosanitary status as a final product, there are still risks associated with the dissemination of pests through the movement of unsanitary feedstock, even at the local scale. Several countries in Europe have analyzed the specific phytosanitary risks of diseased and infested wood in the pellet industry. The results of our literature review indicate, however, that these risks have not been holistically evaluated for the northeastern US. We found that research is needed that matches phytosanitary standards for individual pest species, silvicultural techniques, and methods of operationalizing the use of this feedstock in an economically feasible way. Potential phytosanitary risk mitigation strategies include modifying harvesting activities based on pest dynamics, on-site comminution, and local processing of feedstock within pest quarantine zones. Policies will need to maintain phytosanitary standards and support economic incentives to continue expanding the use of pest-affected salvage wood while also taking into account the high potential costs of human error. Given the expected increase in forest pests in a changing climate and globalizing economy in the northeastern US, the drive for alternative energy sources, and the increase in the use of biomass for energy, our study recommends that the risks and opportunities of salvaged wood from pest events be further investigated.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This work was supported by the Vermont Clean Energy Fund [project number 035685] and the USDA Forest Service Northeastern States Research Cooperative [grant number], and the USDA Forest Service [grant number 14-CA-11420004-036].

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.foreco.2020.118415>.

References

- Alien Forest Pest Explorer (AFPE) | National Agricultural Library, (n.d.). <https://data.nal.usda.gov/dataset/alien-forest-pest-explorer-afpe> (accessed June 3, 2019).
- Allen, E., Noseworthy, M., Ormsby, M., 2017. Phytosanitary measures to reduce the movement of forest pests with the international trade of wood products. *Biol. Invasions* 19, 3365–3376. <https://doi.org/10.1007/s10530-017-1515-0>.
- Barrette, J., Thiffault, E., Saint-Pierre, F., Wetzell, S., Duchesne, I., Krigstin, S., 2015. Dynamics of dead tree degradation and shelf-life following natural disturbances: can salvaged trees from boreal forests “fuel” the forestry and bioenergy sectors? *Forestry* 88, 275–290. <https://doi.org/10.1093/forestry/cpv007>.
- Barrette, J., Thiffault, E., Achim, A., Junginger, M., Pothier, D., De Grandpré, L., 2017. A financial analysis of the potential of dead trees from the boreal forest of eastern Canada to serve as feedstock for wood pellet export. *Appl. Energy* 198, 410–425. <https://doi.org/10.1016/j.apenergy.2017.03.013>.
- Belanger, R.P., Hedden, R.L., Lorio, P.L., 1993. Management strategies to reduce losses from the Southern Pine Beetle. *South J. Appl. For.* 17, 150–154. <https://doi.org/10.1093/sjaf/17.3.150>.
- Batidzirai, B., van der Hilst, F., Meerman, H., Junginger, M.H., Faaij, A.P.C., 2014. Optimization potential of biomass supply chains with torrefaction technology. *Biofuels*. *Bioprod. Bioref.* 8, 253–282. <https://doi.org/10.1002/bbb.1458>.
- Brashaw, B.K., Ross, R.J., Wang, X., Wiemann, M.C., 2010. Wood Utilization Options for Urban Trees Infested by Invasive Species. University of Minnesota. <https://pdfs.semanticscholar.org/b2e7/db93a545557ff5f6e59af53db8793437f2d.pdf> (accessed October 9, 2017).
- Buchholz, T., Keeton, W.S., Gunn, J.S., 2019. Economics of integrated harvests with biomass for energy in non-industrial forests in the northeastern US forest. *Forest Policy and Economics* 109, 102023. <https://doi.org/10.1016/j.forpol.2019.102023>.

- Brantley, S.T., Mayfield, A.E., Jetton, R.M., Miniati, C.F., Zietlow, D.R., Brown, C.L., Rhea, J.R., 2017. Elevated light levels reduce hemlock woolly adelgid infestation and improve carbon balance of infested eastern hemlock seedlings. *For. Ecol. Manage.* 385, 150–160. <https://doi.org/10.1016/j.foreco.2016.11.028>.
- Clarke, S.R., Nowak, J.T., 2009. Southern Pine Beetle, second ed., US Forest Service.
- Dajoz, R., 2000. Insects and forests: the role and diversity of insects in the forest environment. Intercept Limited, Andover, UK <https://www.cabdirect.org/cabdirect/abstract/20001113139> (accessed August 29, 2018).
- Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate change and forest disturbances. *Bioscience* 51, 723–734. [https://doi.org/10.1641/0006-3568\(2001\)051\[0723:CCAFD\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO;2).
- Dale, V.H., Kline, K.L., Marland, G., Miner, R.A., 2015. Ecological objectives can be achieved with wood-derived bioenergy. *Front. Ecol. Environ.* 13, 297–299. <https://doi.org/10.1890/15.WB.011>.
- Dale, V.H., Kline, K.L., Parish, E.S., Cowie, A.L., Emory, R., Malmshier, R.W., Slade, R., (Tat) SMITH, C.T., (BEN) Wigley, T.B., Bentsen, N.S., Berndes, G., Bernier, P., Brandão, M., Chum, H.L., Diaz-Chavez, R., Egnell, G., Gustavsson, L., Schweinle, J., Stupak, I., Trianosky, P., 2017. Status and prospects for renewable energy using wood pellets from the southeastern United States. *GCB Bioenergy*. 9, 1296–1305.
- Dale, V.H., Parish, E., Kline, K.L., Tobin, E., 2017b. How is wood-based pellet production affecting forest conditions in the southeastern United States? *For. Ecol. Manage.* 396, 143–149. <https://doi.org/10.1016/j.foreco.2017.03.022>.
- Dodds, K.J., Aoki, C.F., Arango-Velez, A., Cancelliere, J., D'Amato, A.W., DiGirolomo, M.F., Rabaglia, R.J., 2018. Expansion of Southern Pine Beetle into Northeastern Forests: Management and Impact of a Primary Bark Beetle in a New Region. *J. For.* 116, 178–191. <https://doi.org/10.1093/jofore/fvx009>.
- Dukes, J.S., Pontius, J., Orwig, D., Garnas, J.R., Rodgers, V.L., Brazee, N., Cooke, B., Theoharides, K.A., Stange, E.E., Harrington, R., Ehrenfeld, J., Gurevitch, J., Lerdau, M., Stinson, K., Wick, R., Ayres, M., 2009. Responses of insect pests, pathogens, and invasive plant species to climate change in the forests of northeastern North America: What can we predict? This article is one of a selection of papers from NE Forests 2100: A Synthesis of Climate Change Impacts on Forests of the Northeastern US and Eastern Canada. *Can. J. For. Res.* 39, 231–248. <https://doi.org/10.1139/X08-171>.
- Egnell, G., Paré, D., Thiffault, E., Lamers, P., 2016. Chapter 4 - Environmental Sustainability Aspects of Forest Biomass Mobilisation, in: *Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes*, Academic Press, pp. 50–67. Doi: 10.1016/B978-0-12-804514-5.00004-4.
- Increase in wood as main source of household heating most notable in the Northeast - Today in Energy - U.S. Energy Information Administration (EIA), (n.d.). <https://www.eia.gov/todayinenergy/detail.php?id=15431> (accessed September 23, 2018).
- EPPO, 2015. EPPO Study on wood commodities other than round wood, sawn wood and manufactured items, EPPO Paris. https://www.eppo.int/PUBLICATIONS/TD-1071-EPPO-Study_on_wood_commodities.pdf (accessed November 28, 2017).
- Evenden, M.L., Silk, P.J., 2016. The influence of Canadian research on semiochemical-based management of forest insect pests in Canada, *Canadian Entomologist*. Ottawa 148, S170–S209. <https://doi.org/10.4039/tce.2015.17>.
- Everett, R.A., 2000. Patterns and pathways of biological invasions. *Trends Ecol. Evol.* 15, 177–178.
- Food and Agriculture Organization (FAO), 2011. Guide to implementation of phytosanitary standards in forestry. <http://www.fao.org/3/a-i2080e.pdf> (accessed November 30, 2017).
- Fitzpatrick, M.C., Preisser, E.L., Porter, A., Elkinton, J., Ellison, A.M., 2012. Modeling range dynamics in heterogeneous landscapes: invasion of the hemlock woolly adelgid in eastern North America. *Ecol. Appl.* 22, 472–486. <https://doi.org/10.1890/11-0009.1>.
- Flower, C.E., Knight, K.S., Rebbeck, J., Gonzalez-Meler, M.A., 2013. The relationship between the emerald ash borer (*Agilus planipennis*) and ash (*Fraxinus* spp.) tree decline: Using visual canopy condition assessments and leaf isotope measurements to assess pest damage. *For. Ecol. Manage.* 303, 143–147. <https://doi.org/10.1016/j.foreco.2013.04.017>.
- Foster, D.R., Orwig, D.A., 2006. Preemptive and Salvage Harvesting of New England Forests: When Doing Nothing Is a Viable Alternative. *Conserv. Biol.* 20, 959–970. <https://doi.org/10.1111/j.1523-1739.2006.00495.x>.
- Gan, J., 2004. Risk and damage of southern pine beetle outbreaks under global climate change. *For. Ecol. Manage.* 191, 61–71. <https://doi.org/10.1016/j.foreco.2003.11.001>.
- Glesne, C., Peshkin, A., 1992. Becoming qualitative researchers: an introduction. Longman, White Plains, N.Y.
- Goltsev, V., Tolonen, T., Syuney, V., Dahlin, B., Gerasimov, Y., Karvinen, S., 2012.. Wood harvesting and logistics in Russia-focus on research and business opportunities, Working Papers of the Finnish. Forest Res. Inst. 221.
- Graphics, Drax. (n.d.). <https://www.drax.com/media/graphics/> (accessed September 23, 2018).
- Guo, M., Song, W., Buhain, J., 2015. Bioenergy and biofuels: History, status, and perspective. *Renew. Sustain. Energy Rev.* 42, 712–725. <https://doi.org/10.1016/j.rser.2014.10.013>.
- Haack, R.A., Jendak, E., Houping, L., Marchant, K.R., Petrice, T.R., Poland, T.M., Ye, H., 2002. The emerald ash borer: a new exotic pest in North America, Newsletter of the Michigan Entomological Society. Vol. 47, No. 3 & 4, P.1-5. 1. <https://www.fs.usda.gov/treesearch/pubs/11858> (accessed June 3, 2019).
- Haack, R.A., Baranchikov, Y.N., Bauer, L.S., Poland, T., 2015. Biology of emerald ash borer parasitoids, In: Van Driesche, R.G., Reardon, R.C., Eds. *Biology and Control of Emerald Ash Borer*. FHTET-2014-09. Morgantown, WV: US Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team: 1-15. Chapter 6, pp. 97–112.
- Havill, N.P., Montgomery, M., 2008. The Role of Arboreta in Studying the Evolution of Host Resistance to the Hemlock Woolly Adelgid. <http://arnoldia.arboretum.harvard.edu/pdf/issues/2008-65-3-Arnoldia.pdf> (accessed December 22, 2017).
- Havill, N.P., Vieira, L.C., Salom, S.M., 2014. Biology and control of hemlock woolly adelgid, USDA Forest Service, FHTET. 5. http://www.dcnr.pa.gov/cs/groups/public/documents/document/dcnr_20029649.pdf (accessed September 1, 2015).
- Hayhoe, K., Wake, C.P., Huntington, T.G., Luo, L., Schwartz, M.D., Sheffield, J., Wood, E., Anderson, B., Bradbury, J., DeGaetano, A., Troy, T.J., Wolfe, D., 2007. Past and future changes in climate and hydrological indicators in the US Northeast. *Clim. Dyn.* 28, 381–407. <https://doi.org/10.1007/s00382-006-0187-8>.
- Hlásny, T., Turčáni, M., 2009. Insect Pests as Climate Change Driven Disturbances in Forest Ecosystems. In: Štrélcová, K., Mátyás, C., Kleidon, A., Lapin, M., Matejka, F., Blaženc, M., Škvarenina, J., Holécý, J. (Eds.), *Bioclimatology and Natural Hazards*. Springer, Netherlands, Dordrecht, pp. 165–177. https://doi.org/10.1007/978-1-4020-8876-6_15.
- Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tschamrke, T., 2007. Importance of pollinators in changing landscapes for world crops. *Proc Biol Sci.* 274, 303–313. <https://doi.org/10.1098/rspb.2006.3721>.
- Koppinga, J., Moraal, L.G., Verwer, C.C., Clerckx, A.P.P.M., 2010. Phytosanitary risks of wood chips, Wageningen Alterra UR, The Netherlands. <http://library.wur.nl/WebQuery/wurpubs/395692> (accessed October 9, 2017).
- Kühmaier, M., Erber, G., Kanizian, C., Holzleitner, F., Stampfer, K., 2016. Comparison of costs of different terminal layouts for fuel wood storage. *Renew. Energy* 87, 544–551. <https://doi.org/10.1016/j.renene.2015.10.048>.
- Lamers, P., Thiffault, E., Paré, D., Junginger, M., 2013. Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. *Biomass Bioenergy* 55, 212–226. <https://doi.org/10.1016/j.biombioe.2013.02.002>.
- Lattimore, B., Smith, C.T., Titus, B.D., Stupak, I., Egnell, G., 2009. Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. *Biomass Bioenergy* 33, 1321–1342. <https://doi.org/10.1016/j.biombioe.2009.06.005>.
- Lesk, C., Coffel, E., D'Amato, A.W., Dodds, K., Horton, R., 2017. Threats to North American forests from southern pine beetle with warming winters. *Nat. Clim. Change* 7, 713–717. <https://doi.org/10.1038/nclimate3375>.
- Levine, J.M., D'Antonio, C.M., 2003. Forecasting Biological Invasions with Increasing International Trade. *Conserv. Biol.* 17, 322–326. <https://doi.org/10.1046/j.1523-1739.2003.02038.x>.
- Levesque, C., Kingsley, E., 2017. Today's Timber Markets: Who Will Buy the Low-Grade Wood? 6. Forest notes.
- Liebholt, A.M., McCullough, D.G., Blackburn, L.M., Frankel, S.J., Holle, B.V., Aukema, J.E., 2013. A highly aggregated geographical distribution of forest pest invasions in the USA. *Divers. Distrib.* 19, 1208–1216. <https://doi.org/10.1111/ddi.12112>.
- Logan, J.A., Régnière, J., Powell, J.A., 2003. Assessing the impacts of global warming on forest pest dynamics. *Front. Ecol. Environ.* 1, 130–137. [https://doi.org/10.1890/1540-9295\(2003\)001\[0130:ATOGW\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2003)001[0130:ATOGW]2.0.CO;2).
- Looney, C.E., D'Amato, A.W., Palik, B.J., Slesak, R.A., 2015. Overstory treatment and planting season affect survival of replacement tree species in emerald ash borer threatened *Fraxinus nigra* forests in Minnesota, USA. *Canadian J. Forest Res.* 45, 1728–1738. <https://doi.org/10.1139/cjfr-2015-0129>.
- Losey, J.E., Vaughan, M., 2006. The economic value of ecological services provided by insects. *Bioscience* 56, 311–323. [https://doi.org/10.1641/0006-3568\(2006\)56\[311:TEVOES\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2).
- Lovett, G.M., Canham, C.D., Arthur, M.A., Weathers, K.C., Fitzhugh, R.D., 2006. Forest Ecosystem Responses To Exotic Pests And Pathogens in Eastern North America. *Bioscience* 56, 395–405. [https://doi.org/10.1641/0006-3568\(2006\)56\[0395:FERTEP\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2006)56[0395:FERTEP]2.0.CO;2).
- Lovett, G.M., Weiss, M., Liebhold, A.M., Holmes, T.P., Leung, B., Lambert, K.F., Orwig, D.A., Campbell, F.T., Rosenthal, J., McCullough, D.G., Wildova, R., Ayres, M.P., Canham, C.D., Foster, D.R., LaDeau, S.L., Weldy, T., 2016. Nonnative forest insects and pathogens in the United States: Impacts and policy options. *Ecol. Appl.* 26, 1437–1455. <https://doi.org/10.1890/15-1176>.
- Maciejewska, A.K., Veringa, H., Sanders, J.P.M., Petevs, S.D., 2006. Co-firing of biomass with coal: constraints and role of biomass pretreatment, Office for Official Publications of the European Communities, Luxembourg. <http://library.wur.nl/WebQuery/wurpubs/364651> (accessed November 2, 2017).
- McCullough, D., Poland, T., 2015. Evaluation of Chipping and Heat Treatment to Control Emerald Ash Borer - EAB - Invasive Species - Forest Disturbance Processes -, USDA Forest Service NRS. https://www.nrs.fs.fed.us/disturbance/invasive_species/eab/control_management/chipping_heat/ (accessed October 13, 2017).
- McCullough, D.G., Poland, T.M., Cappaert, D., Clark, E.L., Fraser, I., Mastro, V., Smith, S., Pell, C., 2007. Effects of chipping, grinding, and heat on survival of emerald ash borer, *Agilus planipennis* (Coleoptera: Buprestidae), in chips. *J. Econ. Entomol.* 100, 1304–1315.
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. PRISMA Group, Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med.* 6, e1000097. <https://doi.org/10.1371/journal.pmed.1000097>.
- Muzika, R.M., 2017. Opportunities for silviculture in management and restoration of forests affected by invasive species. *Biol. Invasions* 19, 3419–3435. <https://doi.org/10.1007/s10530-017-1549-3>.
- Muzika, R.M., Liebhold, A.M., 2000. A critique of silvicultural approaches to managing defoliating insects in North America. *Agric. For. Entomol.* 2, 97–105.
- Nicholls, D.L., Halbrook, J.M., Benedum, M.E., Han, H.-S., Lowell, E.C., Becker, D.R., Barbour, R.J., 2018. Socioeconomic Constraints to Biomass Removal from Forest Lands for Fire Risk Reduction in the Western U.S., Forests; Basel. 9, 264. <http://dx.doi.org/10.3390/f9050264>.
- Orwig, D.A., Kittredge, D., 2005. Silvicultural options for managing hemlock forests

- threatened By Hemlock Woolly Adelgid. *Forest Health Technol. Enterprise Team* 212–217.
- Parker, B.L., Skinner, M., Gouli, S., Ashikaga, T., 1998. Survival of Hemlock Woolly Adelgid (Homoptera: Adelgidae) at Low Temperatures. *Forest Science*. 44. <http://docserv.ingentaconnect.com/deliver/connect/saf/0015749x/v44n3/s10.pdf?expires=1441120334&id=82627672&titleid=4023&accname=University+of+Vermont&checksum=A99E1498A1205015226BCCE819B321B4>.
- Parker, B.L., Skinner, M., Gouli, S., Ashikaga, T., Teillon, B.H., 1999. Low Lethal Temperature for Hemlock Woolly Adelgid (Homoptera: Adelgidae). *Environ. Entomol.* 28, 1085–1091.
- Paradis, A., Elkinton, J., Hayhoe, K., Buonaccorsi, J., 2008. Role of winter temperature and climate change on the survival and future range expansion of the hemlock woolly adelgid (*Adelges tsugae*) in eastern North America. *Mitig. Adapt. Strateg. Glob. Change* 13, 541–554. <https://doi.org/10.1007/s11027-007-9127-0>.
- Pellet Fuels Institute, PFI Standards Program, (n.d.). <http://www.pelletheat.org/pfi-standards> (accessed October 13, 2017).
- Petrice, T.R., Haack, R.A., 2011. Effects of cutting time, stump height, and herbicide application on ash (*Fraxinus* spp.) stump sprouting and colonization by emerald ash borer (*Agrilus planipennis*). *North. J. Appl. For.* 28, 79–83.
- Pickering, C., Byrne, J., 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. *Higher Education Research & Development*. 33, 534–548. <https://doi.org/10.1080/07294360.2013.841651>.
- Pullin, A.S., Stewart, G.B., 2006. Guidelines for systematic review in conservation and environmental management. *Conserv. Biol.* 20, 1647–1656. <https://doi.org/10.1111/j.1523-1739.2006.00485.x>.
- Qin, X., Keefe, R.F., Daugaard, D.E., 2018. Small Landowner Production of Pellets from Green, Beetle-Killed, and Burned Lodgepole Pine. *Energies* 11, 648. <https://doi.org/10.3390/en11030648>.
- Safranyik, L., Wilson, B., 2006. The mountain pine beetle: a synthesis of biology, management, and impacts on lodgepole pine, in: *The Mountain Pine Beetle – A Synthesis of Biology, Management, and Impacts in Lodgepole Pine*, Canadian Forest Service, Pacific Forestry Centre.
- Schroeder, L.M., 2008. Insect Pests and Forest Biomass for Energy, in: *Sustainable Use of Forest Biomass for Energy: A Synthesis with Focus on the Baltic and Nordic Region*, Springer, Dordrecht, The Netherlands, pp. 109–124.
- Schowalter, T.D., Noriega, J.A., Tscharnke, T., 2018. Insect effects on ecosystem services—Introduction. *Basic Appl. Ecol.* 26, 1–7. <https://doi.org/10.1016/j.baec.2017.09.011>.
- Skinner, M., Parker, B.L., Gouli, S., Ashikaga, T., 2003. Regional responses of hemlock woolly adelgid (Homoptera: Adelgidae) to low temperatures. *Environ. Entomol.* 32, 523–528.
- Spelter, H., Toth, D., 2009. North America's wood pellet sector, USDA Forest Service Forest Products Lab. https://www.msuxextension.org/forestry/WB2E/Pellets/fpl_rp656.pdf (accessed October 8, 2017).
- Stennes, B.K., Niquidet, K., van Kooten, G.C., 2010. Implications of Expanding Bioenergy Production from Wood in British Columbia: An Application of a Regional Wood Fiber Allocation Model. *Forest Sci.* 56, 366–378.
- Stupak, I., Asikainen, A., Jonsell, M., Karlton, E., Lunnan, A., Mizaraité, D., Pasanen, K., Pärn, H., Raulund-Rasmussen, K., Röser, D., Schroeder, M., Varnagiryte, I., Vilkriste, L., Callesen, I., Clarke, N., Gaitnieks, T., Ingerslev, M., Mandre, M., Ozolincius, R., Saarsalmi, A., Armolaitis, K., Helmisaari, H.-S., Indriksons, A., Kairiukstis, L., Katzensteiner, K., Kukkola, M., Ots, K., Ravn, H.P., Tamminen, P., 2007. Sustainable utilisation of forest biomass for energy—Possibilities and problems: Policy, legislation, certification, and recommendations and guidelines in the Nordic, Baltic, and other European countries. *Biomass and Bioenergy* 31, 666–684. <https://doi.org/10.1016/j.biombioe.2007.06.012>.
- Thrän, D., Peetz, D., Schaubach, K., 2017. Global Wood Pellet Industry and Trade Study 2017, IEA Bioenergy. http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-july-2017.pdf (accessed October 8, 2017).
- Tolko Industries. B.C. partnership to provide wood feedstock for PBEC pellet mill. *Biomassmagazine.com*, (2014). <http://biomassmagazine.com/articles/10384/b-c-partnership-to-provide-wood-feedstock-for-pbec-pellet-mill> (accessed May 3, 2019).
- Turchin, P., Thoeny, W.T., 1993. Quantifying dispersal of southern pine beetles with mark-recapture experiments and a diffusion model. *Ecol. Appl.* 3, 187–198. (accessed June 3, 2019). <https://www.fs.usda.gov/treesearch/pubs/965>.
- US Energy Information Administration, 2014. Increase in wood as main source of household heating most notable in the Northeast, Today in Energy. <https://www.eia.gov/todayinenergy/detail.php?id=15431> (accessed May 18, 2020).
- USDA, 2014. Miscellaneous and Processed Products Import Manual. https://www.aphis.usda.gov/import_export/plants/manuals/ports/downloads/miscellaneous.pdf (accessed November 30, 2017).
- van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasiński, K.J., 2011. Biomass upgrading by torrefaction for the production of biofuels: a review. *Biomass Bioenergy* 35, 3748–3762. <https://doi.org/10.1016/j.biombioe.2011.06.023>.
- Victorsson, J., Jonsell, M., 2013. Ecological traps and habitat loss, stump extraction and its effects on saproxylic beetles. *For. Ecol. Manage.* 290, 22–29. <https://doi.org/10.1016/j.foreco.2012.06.057>.
- Vose, J.M., Wear, D.N., Mayfield, A.E., Dana Nelson, C., 2013. Hemlock woolly adelgid in the southern Appalachians: control strategies, ecological impacts, and potential management responses. *For. Ecol. Manage.* 291, 209–219. <https://doi.org/10.1016/j.foreco.2012.11.002>.
- Walker, T., Cardellicchio, P., Gunn, J.S., Saah, D.S., Hagan, J.M., 2013. Carbon accounting for Woody Biomass from Massachusetts (USA) managed forests: a framework for determining the temporal impacts of wood biomass energy on atmospheric greenhouse gas levels. *J. Sustainable For.* 32, 130–158. <https://doi.org/10.1080/10549811.2011.652019>.
- Waring, K.M., O'Hara, K.L., 2005. Silvicultural strategies in forest ecosystems affected by introduced pests. *For. Ecol. Manage.* 209, 27–41. <https://doi.org/10.1016/j.foreco.2005.01.008>.
- Wei, X., Wu, Y., Reardon, R., Sun, T.-H., Lu, M., Sun, J.-H., 2007. Biology and damage traits of emerald ash borer (*Agrilus planipennis* Fairmaire) in China. *Insect Science*. 14, 367–373. <https://doi.org/10.1111/j.1744-7917.2007.00163.x>.
- Weed, A.S., Ayres, M.P., Hicke, J.A., 2013. Consequences of climate change for biotic disturbances in North American forests. *Ecol. Monogr.* 83, 441–470. <https://doi.org/10.1890/13-0160.1>.
- Whalley, S., Klein, S.J.W., Benjamin, J., 2017. Economic analysis of woody biomass supply chain in Maine. *Biomass Bioenergy* 96, 38–49. <https://doi.org/10.1016/j.biombioe.2016.10.015>.
- Wood and Pellet Heating | Department of Energy, (n.d.). <https://www.energy.gov/en-ergysaver/home-heating-systems/wood-and-pellet-heating> (accessed August 18, 2018).
- Yemshanov, D., McKenney, D.W., Fraleigh, S., McConkey, B., Huffman, T., Smith, S., 2014. Cost estimates of post harvest forest biomass supply for Canada. *Biomass Bioenergy* 69, 80–94. <https://doi.org/10.1016/j.biombioe.2014.07.002>.