resources

MDPI

Review

Forest Health Management and Detection of Invasive Forest Insects

Kaelyn Finley and Sophan Chhin *

Department of Forestry, Michigan State University, 126 Natural Resources Building, East Lansing, MI 48824-1222, USA; finleyk5@msu.edu
* Correspondence: chhin@msu.edu; Tel.: +1-517-353-7251

Academic Editor: Thomas J. Straka
Received: 9 February 2016; Accepted: 28 April 2016; Published: 7 May 2016

Abstract: The objectives of this review paper are to provide an overview of issues related to forest health and forest entomology, explain existing methods for forest insect pest detection, and provide background information on a case study of emerald ash borer. Early detection of potentially invasive insect species is a key aspect of preventing these species from causing damage. Invasion management efforts are typically more feasible and efficient if they are applied as early as possible. Two proposed approaches for detection are highlighted and include dendroentomology and near infrared spectroscopy (NIR). Dendroentomology utilizes tree ring principles to identify the years of outbreak and the dynamics of past insect herbivory on trees. NIR has been successfully used for assessing various forest health concerns (primarily hyperspectral imaging) and decay in trees. Emerald ash borer (EAB) (*Agrilus planipennis*), is a non-native beetle responsible for widespread mortality of several North American ash species (*Fraxinus* sp.). Current non-destructive methods for early detection of EAB in specific trees are limited, which restricts the effectiveness of management efforts. Ongoing research efforts are focused on developing methods for early detection of emerald ash borer.

Keywords: *Agrilus planipennis*; dendrochronology; detection; emerald ash borer; forest health; *Fraxinus* spp.; near-infrared spectroscopy

1. Introduction

Non-native, invasive species are one of the greatest threats to biodiversity and ecosystem stability worldwide [1,2]. Even the most remote forests have the potential risk of exotic introductions due to globalization, continually shifting trade patterns, and climate change [1,3]. Invasive phytophagous (plant feeding) insects also cause substantial economic losses in the United States, particularly to municipal governments and homeowners [2]. The vast majority of exotic introductions fail to establish or have little impact, but some are considered invasive if they cause catastrophic changes to ecosystem structure and function [1,4]. The term invasive is typically associated with non-native species causing severe damage, however, many introduced species are not considered invasive in their new habitat. While select species of nematodes, fungi, bacteria, viruses, plants, animals, insects and other arthropods have all been classified as non-native, invasive species, the main focus of this paper will be on invasive, forest insects. Primary reasons why an insect can become invasive in a new habitat include their arrival without natural predators, parasitoids, and parasites, and the new host plants lacking co-evolved, natural defenses [1,5,6]. Many invasive insects are not detected until well after they have established and begin to spread in their new habitat. Examples of exotic insect species considered to be invasive in North American forests include: emerald ash borer (EAB) (*Agrilus planipennis*), gypsy moth (*Lymantria dispar* L.), and hemlock woolly adelgid (*Adelges tsugae*) [2,7]. The objectives of this review paper are to provide an overview of issues related to forest health and forest entomology, explain existing techniques for forest insect pest detection, and provide background information on a case study of emerald ash borer.

2. Forest Health Overview

Definitions of forest health are broadly varied but can generally be classified as either utilitarian or ecological [8]. Several definitions of forest health include: "a fully functioning community of plants and animals and their physical environment; an ecosystem in balance; a forest resilient to change; the ability of forest ecosystems to recover from natural and human stressors; and a condition where biotic and abiotic influences on forests do not threaten management objectives now and in the future" [5]. The Society of American Foresters defines forest health as "the perceived condition of a forest derived from concerns about such factors as its age, structure, composition, function, vigor, presence of unusual levels of insects or disease, and resilience to disturbance" [9]. With multiple and often contradictory definitions of "Forest Health", to reduce misunderstandings (particularly for environmental policy and management), Raffa *et al.* [10] recommends using the term when describing how well ecosystems function within their historical range of variability and using modifiers when including human objectives when describing a forest. Ultimately, defining forest health is a human construct and to describe a forest as "healthy" depends on management objectives and ecosystem processes.

A quantitative, ecologically based concept for describing forest health is the idea of baseline mortality [11,12]. Baseline mortality is the number of stems in a specified size class that must die in order for population stability, and is often represented by a negative exponential (more small trees and less large trees) [11,12]. Mortality can be achieved naturally through competition or disturbance, or by anthropogenic factors. Disturbances are events that alter the structure, composition, or function of an ecosystem by increasing the availability of limiting resources, and traditional types include native insects and diseases, fire, drought, and invasive species [3,5]. While disturbances harm individual organisms, they can be an essential and normal component of overall ecosystem health [10]. For a forest to be considered healthy, a proposed description is for it to be both sustainable and productive [9]. A sustainable forest has been defined as "one that maintains a stable diameter distribution or structure, and has a balanced relationship between growth and mortality; a forest in which observed mortality is not significantly above or below baseline mortality" [9]. A productive forest is one that meets management objectives [9]. As they are not within their historic range of variability, intensively managed plantation forests are generally not considered as healthy ecosystems, but if they meet management objectives, they can be sustainable [10]. Forest health management does not focus on individual organisms or species, instead it is considered in an ecosystem or landscape level [5,8,10].

3. Causes and Symptoms of Forest Health Issues

Many forest health problems can be induced by direct human action [9]. Species loss, insect and disease epidemics, excessive wildfires, air pollution, water quality problems, impacted wildlife, nutrient imbalances, and soil and watershed damage are some of the main issues associated with anthropogenic forest health problems [5]. Examples of human actions that negatively impact forest health are past and current land use activities, fire suppression, pollution, anthropogenic climate change, desertification, introduction of invasive species, and recreational activities [9,10]. Forested areas have seen an increase in land use and management over the previous two centuries resulting in land cover conversion and reversion to earlier successional stages [13]. These past management activities have altered ecosystem structure and function which often results in increases in the severity and impact of tree diseases and insects [14]. Urban trees are particularly predisposed to stress, as they are often planted in unfavorable sites, grow in compacted soils, have high exposure to pollution, are often planted as monocultures, and are physically damaged by human actions [15,16].

Disease is defined as "a chronic condition or irritation that prevents the affected host from reaching its maximum genetic potential" and can be caused by biotic or abiotic causal agents [17]. Biotic causal agents of disease are broadly referred to as pathogens and include fungi, oomycota, bacteria, viruses, plant-pathogenic algae and vascular plants, and nematodes [18]. Insect feeding is mostly limited to short term or localized damage, and insects are generally not a chronic condition [17]. Some species of insects will interact with and transmit pathogens to facilitate a disease [14]. An example is Beech bark disease, where the scale insect, *Cryptococcus fagisuga*, introduces the fungus *Nectria coccinea* to American beech (*Fagus grandifolia*), causing tree decline and mortality [14]. Abiotic causal agents of disease include but are not limited to, nutrient deficiencies, flooding, drought, unfavorable site conditions, and air pollution [17]. A third category of disease are declines (often referred to the decline disease spiral), which only impact populations of mature trees and results from multiple, interacting causal agents grouped into predisposing, inciting, and contributing factors [17,19].

Native insects and pathogens that feed on trees are essential, natural thinning agents that reduce competition through mortality and contribute to overall ecosystem health [10]. Natural disturbance agents (*i.e.*, forest insects) are only considered pests due to human values and expectations, and the term "pest" has been defined as, "an organism that interferes with our management objectives" [10]. Tree mortality due to native organisms is often not widespread, but there are cases of naturally occurring, periodic outbreaks of native insects, such as the spruce beetle (*Dendroctonus rufipennis*), the mountain pine beetle (*Dendroctonus ponderosae*), spruce budworms (*Choristoneura fumiferan*a and *C. occidentalis*), and the southern pine beetle (*D. frontalis*) in North America which can cause extensive tree mortality [17,20]. While most widespread outbreaks of native forest insects can be severe, often they are reoccurring and natural parts of the ecosystem process [17,20]. However, in the case of the mountain pine beetle, the recent increase in frequency and severity of outbreaks has been associated with climate change, overstocked stands, fire suppression (which has increased the proportion of overmature, susceptible trees in these forests), and prolonged drought [5,20].

The term invasive species in this paper will refer to non-indigenous organisms whose introduction was facilitated by humans, and which are currently causing significant ecological and or economic harm as defined by Parry and Teale [3]. There are several key stages of a biological invasion by an invasive species from its native region to the area it is introduced [21]. The sequential stages of invasion include arrival (transportation from native habitat to new location), establishment (population growth), and spread (movement of species in the introduced habitat to new areas) [7]. However, the actual stages and terminology is not always agreed upon and using the stage based method for explaining invasions can imply that they only occur one at a time [21]. For each phase of an invasion, the organism is faced with barriers and ultimately only a small portion of species from the original source establish and even fewer become invasive in a new habitat ([1,3]. Nearly all non-indigenous introductions today can be classified as human-assisted and the number of introductions has greatly increased with the expansion of international trade [22,23]. However, the establishment rate in the United States has remained relatively constant since around 1860, with an average detection of 2.5 new phytophagous species a year [1]. Many insects are unintentionally transported on infested nursery and seed stock, wood packing material, and lumber that is shipped internationally [24]. The horticultural and ornamental trade industries in particular, are an important pathway for many invasive invertebrates, pathogens and plant species [22]. Invasions of forest insect pests worldwide are directly influenced by continuously changing modes of transportation, shipping practices, shifts in trading patterns, and international plant transport [1,23]. Many countries, including the United States, have established regulatory practices including quarantines and inspections (particularly for borders and ports of entry), in an attempt to prevent exotic introductions [1].

An explanation for the ability of certain non-native insects to become invasive in a new habitat is that plants develop mechanisms for deterring or surviving attack through co-evolution with their herbivores [6,25]. When insects are introduced to new habitats they may be able to feed on hosts due to a lack of suitable defense mechanisms [25]. Another reason for invader success is that when they are introduced to the new habitat, it is often without natural enemies that typically keep their populations in check [25]. The emerald ash borer is a phloem feeding beetle native to Asia that causes widespread mortality of the North American species in the genus *Fraxinus* [26]. To date, the emerald ash borer is considered to be the most destructive forest insect pest in North America [2,26]. The gypsy moth (native to Europe and Asia) is currently the most destructive forest defoliator in the United States and can feed on a wide range of host species [27]. The gypsy moth, like other defoliating insects, mainly causes tree mortality only when severe defoliation occurs consecutively over several years, or in conjunction with additional disturbance factors [2]. The hemlock woolly adelgid (native to Japan) is a sap feeding insect that causes localized decline and mortality of eastern hemlock (*Tsuga Canadensis*) in the eastern United States [2,28].

4. Applied Forest Entomology

Forest entomology is the study of forest insects, both beneficial and those considered pests. Since it was first established, the field has undergone substantial changes and continues to evolve [25,29]. Forest entomology was first developed in Germany in the 1800s and the first member of this field, Julius Theodor Christian (J.T.C.) Ratzeburg is credited as being the "father of forest entomology" [30]. For many years, forest entomology in North America was primarily focused on developing methods of pest control to protect forest resources [25,29]. During the time period from around 1945 to 1965, potent insecticides were widely used to kill forest insect populations [25,30]. Around the 1960s in the United States, the advancement of knowledge in forestry, diminishing old growth forests, and changes in societal values allowed the entire field of forestry to shift from focusing on timber harvesting towards managing forests for both marketable and non-timber values [25]. Entomologists around this time also realized that many forest insects play important ecosystem services and that feeding induced tree mortality is sometimes beneficial for overall forest health [25]. Widespread usage of environmentally persistent insecticides which also had unintended non-target effects were also cause for concern. These changes in societal values, increased scientific knowledge and more frequent exotic introductions have made forest entomology much more complex today than it once was.

At least half of insect species are estimated to be herbivorous (phytophages), but of the 29 insect orders, only nine include or contain species that feed on live plants [31]. These orders include: Thysanoptera (thrips), Orthoptera (crickets, grasshoppers), Phasmatodea (stick insects), Hemiptera (true bugs, aphids, and scale insects), Coleoptera (beetles), Lepidoptera (moths and butterflies), Hymenoptera (ants, wasps, bees, hornets, sawflies), Psocoptera (bark lice), and Diptera (flies) [5,31]. There are 16 orders of insects that include species that eat dead or dying plant material (detrivores, decomposers, and shredders) [31]. For most plant species, multiple insect herbivores can simultaneously exploit almost every part of the plant [31]. Coevolution with insects has allowed trees to develop barriers to herbivory [6,25]. Insect herbivores of living plants can be classified by diet breadth (host range) and feeding guild (similar feeding mechanism of the same resources) [31]. Host ranges include monophagous (limited to feeding on a single species or genus), oligophagous (feeding in a single family for multiple genera), and polyphagous (ability to feed on multiple families of plants) [1,31]. The hemlock woolly adelgid is considered monophagous in North America as it only feeds on trees in the *Tsuga* genus, while the gypsy month (*Lymantria dispar*) is polyphagous as it is capable of feeding on several hundred tree and shrub species in multiple families ([28,32]. In some cases, the diet breadth of a species can change when in its native range compared to where it is non-native [31]. A comprehensive study of the known 450 non-indigenous insect species established in the United States saw that 38% were monophagous, 33% were polyphagous, and 29% were oligophagous [1]. Foliage and sap feeding insects (exophages) make up the majority of non-native introductions to the United States [1]. Concealed feeding guilds (endophages) include stem and wood-borers, fruit borers, seed and pod borers, gall insects, and root feeders [31]. Introductions of endophages, such as phloem feeding and wood boring beetles, have increased recently as they are often transported internationally in wood packing material and lumber [24]. Wood boring and phloem feeding invasive insects are associated with the highest economic and ecological impacts compared to defoliators as they typically cause greater mortality [2].

Outbreaks of forest insects (both native and non-native) are controlled by the components of integrated pest management (IPM): (1) mechanical and physical control; (2) chemical control, (3) biological control [5,21]. Mechanical and physical control involves methods that destroy or remove the insects themselves, or change their habitat so that it is no longer suitable such as silvicultural methods (e.g., thinning) [5]. For example, mass trapping with attractive traps and heat treatment of lumber can be used to kill any insects living in the material [5]. Using chemical treatments alone is often not economically feasible in most forests to reduce insect populations and the negative environmental effects of many pesticides often outweigh the benefits [5]. Semiochemicals are compounds often used by insects during host and/or mate-location and selection [4,5]. Semiochemicals are an important tool for monitoring and detecting native and exotic insects as part of pest management practices [4,5]. Classical biological control involves the importation, release, and establishment of an invasive insect's specialist predators from its native habitat to the new one ([7,25]. Negative impacts have occurred when introducing generalist predators and current methods now incorporate quarantined screening for potential, unintended hosts to avoid introducing a new pest [25]. Integrated pest management is an approach that combines multiple, suitable control methods in order to reduce or manipulate populations to acceptable levels that limit the degree of economic related damage (since complete eradication is rarely feasible) [5,27,31]. An example of a successful integrated pest management program is the slow the spread program for gypsy moth (*Lymantria dispar*) [27]. This program deploys grids of pheromone-baited traps ahead of the population front, and once detected, colonies are delineated and treated [27].

In the United States, the U.S. Department of Agriculture (USDA) Forest Service, Forest Health Monitoring (FHM) established in 1990 is responsible for annually monitoring the status, changes, and trends in national forest conditions [5,33]. The U.S. Forest Service Inventory and Analysis (FIA) Program is responsible for conducting sampling in the FIA national field plot network [33]. The FHM program works with the FIA, and state and Federal Agencies to monitor forest health and to provide information on invasive species and updated conditions of forest insects and diseases [33]. The USDA Forest Service started the Early Detection and Rapid Response program in 2001 for detecting non-indigenous phloem feeding and wood boring insects in the United States [1], and by 2016 this detection list has grown to 355 species [34].

5. Detection Techniques of Invasive Insects

Early detection of potentially invasive insect species is a key aspect of preventing these species from causing damage [3]. In practice, this is difficult and often, non-native species are not detected until after they are already established [3]. Studies have indicated that invasion management efforts are typically more feasible and efficient if they are applied as early as possible [25,35,36]. Eradication may be possible if new colonies of potentially invasive insects are detected early when the insect is still in a limited geographic area, particularly urban areas [25,36]. After initial detection, trace-forwards and trace-backwards are conducted if an interception is associated with a particular commodity. Delimitation surveys are implemented to determine where the invasive insect population is distributed in the new environment [3,37]. Control measures cannot be applied without information of where the insect is located. Detection methods are often specific to the species causing the damage, the life stage under observation and type of damage caused/feeding behavior [3,38]. General survey methods may utilize aerial and ground based surveys; observations of the insect itself; the signs, symptoms, or damage caused by the insect; and baited traps [3]. Trapping detection methods for low population levels typically require effective attractants such as plant compounds or pheromones for the intended species [37]. One example of early detection is the mitigation efforts of gypsy moth, which have been successful in the United States largely due to detection and delimitation of outlying populations using highly effective pheromone traps [37].

Insects that feed within trees are typically more difficult to detect than insects that feed on external tree tissues [35]. In the United States, introductions and detection of non-indigenous phloem feeding and wood boring insects have increased over the past few decades [1]. Bark beetle and wood borer detection methods involve ground surveys in well-roaded areas, aerial surveys for large areas, and the use of host volatile or pheromone baited traps [5]. Attractants are not available for many beetle species and their detection is difficult [4,37]. Recent developments include DNA-based methods. DNA "barcodes" for example, lead to both detection and identification species with 100% accuracy [38]. This method has great potential, but requires the development of global DNA databases for all relevant taxa in order to provide a standardized tool for worldwide use [38]. Locations for implementing insect surveillance methods are also important as a recent study in Italy concluded that detection of non-native wood boring beetles was improved by surveying in wood waste landfills in addition to ports of entry [39]. Dendrochronology has also been used to reconstruct past outbreak dynamics and spread of invasive insect species [40–43], as will be discussed in the following section.

Spectroscopic and imaging techniques have been applied successfully for plant stress detection, particularly in agriculture and have potential for rapid, non-destructive, and cost-effective detection of damaging insects [3]. Hyperspectral imaging is used in agriculture and some forestry applications by acquiring the spectral reflectance in the visible and infrared regions of the electromagnetic spectrum [44]. In particular, studies have shown that hyperspectral remote sensing can produce detailed maps of forest health conditions and species distribution on a landscape scale [45], but require ground-truthing and have limited temporal resolution. There has also been studies looking at the volatile organic compounds (VOC) released by vegetation which are influenced by humidity, temperature, light, soil conditions, fertilization, growth and developmental stage, and insect presence/damage [44,46].

5.1. Dendrochronology

Dendrochronology is the study of tree ring dating to explain surrounding environmental information including climate, disturbance events, stand composition and insect herbivory throughout a tree's lifetime [47]. Previous studies have shown the usefulness of dendrochronological methods for observing the impacts of climate, disturbance events, insects and diseases on radial growth [40,48,49]. In dendrochronology, valid inferences can be made indirectly about the mechanisms of tree response to their environment [50]. Dendroclimatology (a subfield of dendrochronology) is the study of past and present climates using climatic information and tree ring growth [51]. Trees are highly responsive to their surrounding environments and climatic factors (*i.e.*, temperature and precipitation) in particular have been shown to be primary controlling factors on ring growth [47]. Trees growing in different regions are often limited by different climate factors; for example, trees growing in the American Southwest are typically limited by moisture availability while at higher latitudes, temperature is the primary limiting factor [52,53].

Dendroentomology utilizes tree ring principles to identify the years of outbreak and the dynamics of past insect herbivory on trees. While dendrochronological methods have been successfully used to identify past outbreaks and reconstruct the spread of some invasive insects, it is less likely that dendrochronology can be used for early detection of acute insect infestations. Dendrochronological studies have shown that the mountain pine beetle (*Dendroctonus ponderosae* Hopkins), a bark beetle native to North America that occurs primarily on lodgepole pine (*Pinus contorta* Douglas ex Loudon) shows periodic outbreaks approximately every 40 years in central British Columbia [54]. Rentch *et al.* [43] used dendrochronology to relate changes in radial growth with crown condition in eastern hemlock (*Tsuga canadensis*) infested by hemlock woolly adelgid (*Adelges tsugae*). A previous study was conducted on green ash (*Fraxinus pennsylvanica*) to reconstruct the spread of emerald ash borer near the epicenter of initial EAB establishment in North America (southeast Michigan) [40]. Using a systematic grid, Siegert *et al.* [40] collected samples from a geographic area in southeast Michigan (around 1.5 million ha) in order to reconstruct the initial establishment and spread of EAB. Siegert *et al.* [40] concluded that EAB was established in Michigan by the early to mid-1990s, several years before it was officially discovered in 2002. Dendrochronological studies are also more challenging in tropical forest regions because of the lack of seasonality in temperature but seasonality in precipitation can provide the opportunity for examining annual growth dynamics [55,56].

5.2. Near Infrared Spectroscopy

Near-infrared spectroscopy (NIR) is becoming an increasingly popular technique in a wide range of industries (agricultural, pharmaceutical, industrial, wood-products industry and forestry). NIR is an appealing technique as it investigates the vibrational properties of materials rapidly and nondestructively [57]. The near-infrared region is located in the 780 to 2500 nm region of the electromagnetic spectrum between the visible and infrared regions [58]. Modern NIR spectroscopy (post 1960s) incorporates high performance and commercially available spectrometers with multivariate analysis to provide chemical and physical information for both biological and manufactured materials [58]. Compared to chemical analysis, which is destructive and costly for relatively small amounts of samples, NIR can non-destructively analyze bulk materials rapidly with minimal sample preparation [58]. For NIR studies measuring wood, the spectra are either collected in diffuse reflectance or transmission modes [59]. Transmission is typically limited in its application because this method requires more sample preparation such as milling or slicing [59]. Diffuse reflectance has a wider application as it can measure intact, solid samples in addition to samples whose original state has been altered (although changing the physical state of samples will influence spectra) [59]. A NIR diffuse reflectance spectrum is a composite of chemical and physical properties of a material [58]. Diffuse reflectance works by sending a beam of light to the object being measured, where it interacts with the sample before being reflected back to the spectrometer [59]. NIR spectra are unique for every substance, and if two or more samples have similar spectra, it can be assumed that they have similar chemical and physical composition [58]. Conversely, if the spectra of multiple samples are different, it can be assumed that the materials are physically and/or chemically different [58].

In NIR studies, multivariate calibrations are often required for spectral analysis. While there are a wide variety of multivariate analytical methods that are used for NIR analysis, they can be separated between two distinct groups, quantitative and qualitative analysis (for the purposes of this paper we will only discuss qualitative methods). A qualitative method, discriminant analysis, is used for sorting spectra by sample type and applying the technique to compare the different groups [60]. Discriminant analysis is used for NIR spectroscopic analysis in order to qualitatively determine whether a sample is similar or different compared to samples from one or more predetermined groups [60]. Discriminant analysis has been successfully used in several previous NIR studies for classifying spectral samples based on distinct groups [61–63]. Ertlen *et al.* [61] successfully used multiple discriminant analysis to distinguish between grassland and forest soils. Evans *et al.* [62] saw that while discriminant analysis improved the identification of wood from two tree species compared to existing identification methods, classification was still not perfect. Watanabe *et al.* [63] were able to successfully identify intact wood compared to wood with wet-pockets using two different variants of discriminant analysis.

The majority of NIR research done for trees is implemented in the wood products industry for wood structural quality and decay; however this technique is increasingly being explored for alternative applications in forestry [64,65]. NIR studies for assessing various wood properties (*i.e.*, wood density) have been applied to both hardwoods and softwoods [66]. Wood properties are highly influenced by the amount of moisture in the sample, the effects of which can be minimized by oven drying all samples before collecting NIR measurements [59]. While not extensively, NIR has been successfully used for assessing various forest health concerns and decay in trees [45,67,68]. The majority of NIR based studies for tree decline due to insect infestation have measured foliage samples, while studies on decay will measure wood samples [45,67,69–71]. Field-based NIR spectrometers and satellite-based hyperspectral NIR has the potential to detect early stages of hemlock wooly adelgid induced hemlock decline by measuring foliage [69]. Watanabe *et al.* [63] reported that spectroscopy in the visible light and near-infrared ranges (VIS-NIR) could discriminate between wood with wet-pockets and wood free of wet-pockets. To assess oak decline due to outbreaks of the red oak borer (*Enaphalodes rufulus*) a handheld NIR spectrometer measured foliage samples to describe plant stress [67]. However, the widespread implementation of hyperspectral imaging is currently limited by high costs [72]. For example, as of 2015, the costs associated with unmanned aerial vehicles used for hyperspectral imaging can be over $50,000 [72].

Several studies have explored the potential of utilizing hyperspectral imaging for detecting and mapping emerald ash borer infestations [45,73–76]. Bartels *et al.* [75] found that when using hyperspectral images and LIDAR data for identifying hardwood tree species and EAB declining ash trees, misclassification of different tree species occurred. However, they were able to use hyperspectral imagery for classifying multiple ash health categories with accuracy up to 60%–70% [75]. Maps created using hyperspectral imagery and vegetation indices were able to identify five different ash decline classes (due to EAB infestation) at 97% accuracy [45]. A recent case study for EAB detection in Canada using multisourced data (both a variety of commercially available remotely sensed data and archived maps), highlighted that current challenges prevent effective use of hyperspectral technologies for detection and mapping EAB infestation [76]. These challenges include labor intensive and lengthy manual corrections of segmentations, limited data sources, and timing of image acquisitions [76].

6. Case Study: Emerald Ash Borer

The emerald ash borer is a phloem-feeding beetle native to Asia identified in southeast Michigan in 2002 as the cause of extensive decline and mortality of ash (*Fraxinus* spp.) [77]. Current methods in detecting emerald ash borer infestation early and at a large scale are limited, restricting the ability to effectively manage for this insect. It is imperative to develop cost-effective approaches in implementing regional scale methods for early detection of EAB. By using cross-dating techniques on cores collected from the initial infestation area of Detroit, Michigan, dendrochronological data has shown that EAB was established for around 10 years before first being detected [40]. As of 2015, EAB has killed tens of millions of ash trees in the eastern United States as well as parts of Canada and annually causes billions of dollars' worth of damage [2,78]. EAB is not considered a major pest where it is native in Asia, and does not cause widespread mortality of the more resistant Asian ash species including *Fraxinus mandshurica and F. chinensis* [15]. Ongoing research efforts include developing methods for early detection of emerald ash borer [78].

6.1. Life Cycle

The life cycle of an individual emerald ash borer is typically completed in one year, although some individuals may need two years to complete their development [79]. Two year life cycles have been observed on recently infested trees with low population levels of EAB, in areas with cooler climates, or associated with late summer oviposition [26,80]. Adult beetles emerge in May or June leaving behind D-shaped exit holes on the tree and live for about 3 to 6 weeks, during which they feed and mate [81]. The adults are typically more active on warm (>25 °C), sunny days [80]. After feeding on ash foliage for at least two weeks, mated females lay 60 to 80 eggs in bark crevices from late June through August, which hatch within 2 weeks when temperature are around 25 °C [80]. The larvae then chew their way into the bark and create serpentine shaped galleries packed with frass as they feed in the phloem, cambium, and outer xylem [80]. Extensive feeding by the larvae disrupts translocation of nutrients, and can girdle and kill a tree in 2–4 years after crown dieback becomes noticeable [26]. EAB will typically complete 4 instars before overwintering as prepupal larvae in the outer 1–2 cm of sapwood or bark beginning in October [26,81]. Two year life cycles occur when the larvae overwinter as early instars, continue to feed a second summer, and overwinter the second year as prepupae [79]. Pupation will take place from the middle of April through May for about 3 weeks, followed by adult emergence [15]. As the damage is done beneath the bark, infestation is difficult to detect in newly infested trees as there is often a delay between initial infestation and when visual symptoms develop [78].

6.2. Host Species and Spread

Ash is a fast growing woodland tree and has been planted extensively in urban areas which are often unfavorable sites [15]. The 16 endemic species of ash in North America are susceptible to EAB induced mortality in the United States, and potential hosts in the US range from Northern Maine to Southern California [15]. Where EAB is native, it typically only targets stressed or dying species of Asian ash, but has caused high mortality on imported North American ash species [80]. The two most common North American ash species, white (*F. americana*) and green (*F. pennsylvanica*) are taxonomically and economically important, but identification is complicated by their ability to hybridize [82]. While there appears to be strong preference for some species over others, all North American ash species located in its current range have proven to be susceptible to EAB infestation and decline to some extent [26,83,84]. The North American species, blue ash (*Fraxinus quadrangulata* Michx.) can be colonized by EAB but has been shown to have higher resistance compared to other native ash species [84]. The supercooling point for EAB is −35.3 °C: at and below this temperature EAB freezes and dies [83]. It is expected however, that North American EAB distribution will be limited more by host range instead of climate [26]. EAB adults can fly away from the tree where they emerge, but the spread is primarily facilitated by people moving infested ash into uninfested areas [26]. Human transportation of infested ash material further predisposes urban forests for introductions and establishment of EAB [26]. Due to the ability of EAB to spread rapidly, research efforts have focused on identifying and developing new methods for early detection.

Evidence suggests that adult EAB use visual and olfactory cues in locating and selecting hosts [85]. There also appears to be adult preference for rough-barked trees over smooth-barked trees and will generally target trees grown in open conditions compared to shaded conditions [77,86,87]. Adults are also attracted to specific shades of green and purple [88]. Host volatiles produced by ash are attractive to adult beetles and bark sesquiterpenes and green leaf volatiles have been identified [78,89–91]. These volatiles often increase with host stress and girdled ash trees in particular are highly attractive to adult EAB [86,87,89,91].

6.3. Past and Present Detection Methods and Treatment Options

After the discovery of EAB in North America, initial monitoring was based on the visual signs and symptoms of infestation such as D-shaped exit holes left by the emerging adults, longitudinal cracks in the bark over the S-shaped larval galleries, canopy dieback, epicormic shoots and woodpecker damage [90]. Accurate detection and monitoring methods of EAB populations and newly established infestations have been difficult to develop, which greatly hinders the ability to effectively manage for this pest. In addition to the lengthy amount of time before visual symptoms develop, on the ground detection is further complicated by the fact that adult EAB will typically target the upper portion of a tree during the initial infestation [15]. Furthermore, a long range pheromone has not yet been detected for EAB [92]. Two short range, contact pheromones produced by adult emerald ash borer females have been identified that are antennally attractive to the males and have been used to improve trap captures [80,90,93,94]. Currently, key survey methods include the use of external signs and symptoms, green and purple sticky prism traps baited with ash volatile lures, green multi-funnel traps, trap logs, and using girdled trap trees which are an expensive and destructive method [15,88,92,95]. Trap trees involve girdling (removing a band of bark and phloem from around the tree) individual trees which become attractive to the adult beetles [86,87]. After one to two years the tree is felled and debarked in autumn to inspect for EAB larvae and S-shaped galleries [96]. Artificial traps include the sticky prism traps [87,88], double-decker traps [95,97,98], and Lindgren green multi-funnel traps [78,99]. The manufactured sticky prism traps currently used for EAB are visually attractive purple and green made from corrugated plastic covered in sticky glue, which are typically baited with host volatile lures [88,90]. Efforts in the United States include deploying thousands of these baited purple prism traps [100,101]. Purple traps generally catch more females than males, and green prism traps (when hung ~13 m in the canopy) will catch more males than females [90]. Green multi-funnel traps treated with a slippery coating have demonstrated potential as an effective and reusable detection and survey tool [88]. These multi-funnel traps have recently started being deployed in the United States in addition to the purple prism traps [101]. While artificial traps are visually attractive to adult beetles, the effectiveness of traps depends on lure types and combinations and placement of the traps [78]. Improvements to EAB lures are still a focus of EAB detection research and the (Z)-3-hexanol lure is the current recommendation by the USDA APHIS (Animal and Plant Health Inspection Service) for trap deployment [78,88,101]. Girdled trap trees are more likely to detect EAB at low populations compared to artificial baited traps [102]. The study by Ryall *et al.* [103] developed a detection method for urban trees that involves the collection of branches that are subsequently debarked and inspected for EAB feeding activity. Preliminary studies utilizing hyperspectral remote sensing have explored as a potential method for emerald ash borer detection and surveying [45,73,75].

The long-term outlook for North American ash survival does not look promising, but treatment options do exist for high value urban and shade trees and efforts are underway to slow the spread of EAB [104]. Research has shown that even with large EAB populations, some insecticide options can be highly effective in keeping treated trees alive [104]. Some estimates have indicated that the cost of treating high value landscape and urban ash trees with systemic insecticides can be less than if the trees were removed [104]. There are four categories of insecticides that are currently being used to control EAB: (1) systemic insecticides applied as soil injections; (2) systemic insecticides applied as trunk injections; (3) systemic insecticides applied as lower trunk sprays; and (4) protective cover sprays applied to the trunk, branches, foliage [104]. These insecticide treatments are most effective when applied as soon as possible to relatively healthy trees, as trees that have lost more than 50% of its crown are usually too far gone to save [104]. In 2008, a pilot project to slow the impact of EAB, called SLAM (SLow Ash Mortality) was initiated as an integrated strategy for dealing with recently established outlier sites [100]. The SLAM pilot project used girdled ash trees, a systemic insecticide, and removal of ash trees [100]. Long-term conservation of ash by reducing EAB populations in North America have invested in classical biological control and three parasitoids native to China are currently being released in the United States [105]. At this time, the long-term impact of the biological control agents on EAB populations is uncertain [26].

7. Conclusions

The ability to detect and delineate infestations of destructive forest insects is essential for management and mitigation of damage. As current detection methods for individual trees are often destructive, this review evaluated the potential of two non-destructive methods as indicators of emerald ash borer infestation. That is, this review explored the potential of dendrochronology and near-infrared spectroscopy (NIR) as non-destructive indicator tools of emerald ash borer infestation in white ash. Dendrochronology is the study of tree ring dating and is used to explain environmental information (climate, disturbance, stand composition, *etc.*) throughout the lifetime of a tree. Valid inferences can be made using dendrochronology to indirectly explain the ecophysiological mechanisms of a tree's response to its environment including the impact of insects (*i.e.*, dendroentomology). While Dendrochronology can be useful in characterizing past invasions, the potential as a rapid detection tool is less likely. Near-infrared spectroscopy measures the vibrational properties of objects in the near-infrared wavelength range of the electromagnetic spectrum (780–2500 nm) rapidly and non-destructively. NIR provides physical and chemical information by producing a spectrum along the near-infrared wavelength range unique to the measured sample. Cost limiting factors currently restrict the widespread application of NIR for early detection of insect invasions. Future research would be required for further development and refinement of these techniques as detection tools.

Since its discovery in 2002, emerald ash borer (EAB), (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae), has killed millions of ash trees (*Fraxinus* spp.) in the eastern U.S. and parts of Canada, and is continuing to spread throughout North America [26]. Emerald ash borer is considered to be the most destructive invasive insect pest in North America to date [26]. As this exotic insect spreads across the U.S. the economic damage is estimated to reach billions of dollars [2]. Research is ongoing for improvements to existing detection methods and developing new methods of effective EAB detection.

Acknowledgments: We thank Deborah McCullough and Pascal Nzokou for providing comments on a previous version of the manuscript. Funding for this project was provided by Michigan State University (MSU) AgBioResearch (Project # MICL06016), MSU College of Agriculture and Natural Resources, MSU Department of Forestry, and a grant from the U.S. Forest Service (Forest Health and Protection, Project # 12-DG-11420004-208).

Author Contributions: Kaelyn Finley and Sophan Chhin both conceived and designed the paper; Kaelyn Finley led and Sophan Chhin assisted with the literature review; Kaelyn Finley led and Sophan Chhin assisted with writing the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Aukema, J.E.; McCullough, D.G.; Von Holle, B.; Liebhold, A.M.; Britton, K.; Frankel, S.J. Historical accumulation of nonindigenous forest pests in the continental United States. *Bioscience* **2010**, *60*, 886–897. [CrossRef]
2. Aukema, J.E.; Leung, B.; Kovacs, K.; Chivers, C.; Britton, K.O.; Englin, J.; Frankel, S.J.; Haight, R.G.; Holmes, T.P.; Liebhold, A.M.; *et al.* Economic impacts of non-native forest insects in the continental United States. *PLoS ONE* **2011**, *6*. [CrossRef] [PubMed]
3. Parry, D.; Teale, S.A. Alien invasions: The effects of introduced species on forest structure and function. In *Forest Health: An Integrated Perspective*; Castello, J.D., Teale, S.A., Eds.; Cambridge University Press: New York, NY, USA, 2011; pp. 115–162.
4. Brockerhoff, E.G.; Liebhold, A.M.; Richardson, B.; Suckling, D.M. Eradication of invasive forest insects: Concept, methods, costs and benefits. *N. Z. J. For. Sci.* **2010**, *40*, S117–S135.
5. Edmonds, R.L., Agee, J.K., Gara, R.I., Eds.; *Forest Health and Protection*; McGraw-Hill Companies, Inc.: Boston, MA, USA, 2000.
6. Rausher, M.D. Co-evolution and plant resistance to natural enemies. *Nature* **2001**, *411*, 857–864. [CrossRef] [PubMed]
7. Liebhold, A.M.; Tobin, P.C. Population ecology of insect invasions and their management. *Annu. Rev. Entomol.* **2008**, *53*, 387–408. [CrossRef] [PubMed]
8. Kolb, T.E.; Wagner, M.R.; Covington, W.W. Concepts of forest health. *J. For.* **1994**, *92*, 10–15.
9. Teale, S.A.; Castello, J.D. The past as key to the future: A new perspective on forest health. In *Forest Health: An Integrated Perspective*; Castello, J.D., Teale, S.A., Eds.; Cambridge University Press: New York, NY, USA, 2011; pp. 3–16.
10. Raffa, K.F.; Aukema, B.; Bentz, B.J.; Carroll, A.; Erbilgin, N.; Herms, D.A.; Hicke, J.A.; Hofstetter, R.W.; Katovich, S.; Lindgren, B.S.; *et al.* A literal use of "forest health" safeguards against misuse and misapplication. *J. For.* **2009**, *107*, 276–277.
11. Zhang, L.; Rubin, B.D.; Manion, P.D. Mortality: The essence of a healthy forest. In *Forest Health: An Integrated Perspective*; Castello, J.D., Teale, S.A., Eds.; Cambridge University Press: New York, NY, USA, 2011; pp. 17–49.
12. Cale, J.A.; Teale, S.A.; West, J.L.; Zhang, L.I.; Castello, D.R.; Devlin, P.; Castello, J.D. A quantitative index of forest structural sustainability. *Forests* **2014**, *5*, 1618–1634. [CrossRef]
13. Schulte, L.A.; Mladenoff, D.J.; Crow, T.R.; Merrick, L.C.; Cleland, D.T. Homogenization of northern U.S. Great Lakes forests due to land use. *Landsc. Ecol.* **2007**, *22*, 1089–1103. [CrossRef]
14. Castello, J.D.; Leopold, D.J.; Smallidge, P.J. Pathogens, patterns, and processes in forest ecosystems: Pathogens influence and are influenced by forest development and landscape characteristics. *Bioscience* **1995**, *45*, 16–24. [CrossRef]
15. Poland, T.M.; McCullough, D.G. Emerald ash borer: Invasion of the urban forest and the threat to North America's ash resource. *J. For.* **2006**, *104*, 118–124.
16. Gillner, S.; Bräuning, A.; Roloff, A. Dendrochronological analysis of urban trees: Climatic response and impact of drought on frequently used tree species. *Trees* **2014**, *28*, 1079–1093. [CrossRef]
17. Teale, S.A.; Castello, J.D. Regulators and terminators: The importance of biotic factors to a healthy forest. In *Forest Health: An Integrated Perspective*; Castello, J.D., Teale, S.A., Eds.; Cambridge University Press: New York, NY, USA, 2011; pp. 81–114.

18. Sinclair, W.A.; Lyon, H.H. *Diseases of Trees and Shrubs*, 2nd ed.; Cornell University Press: Ithaca, NY, USA, 2005; p. 660.
19. Manion, P.D. *Tree Disease Concepts*, 2nd ed.; Prentice-Hall: Englewood Cliffs, NJ, USA, 1991.
20. Williams, D.W.; Liebhold, A.M. Climate change and the outbreak ranges of two North American bark beetles. *Agric. For. Entomol.* **2002**, *4*, 87–99. [CrossRef]
21. Davis, M.A. *Invasion Biology*; Oxford University Press Inc.: New York, NY, USA, 2009.
22. Liebhold, A.M.; Brockerhoff, E.G.; Garrett, L.J.; Parke, J.L.; Britton, K.O. Live plant imports: The major pathway for forest insect and pathogen invasions of the U.S. *Front. Ecol. Environ.* **2012**, *10*, 135–143. [CrossRef]
23. Liebhold, A.M.; McCullough, D.G.; Blackburn, L.M.; Frankel, S.J.; Von Holle, B.; Aukema, J.E. A highly aggregated geographical distribution of forest pest invasions in the USA. *Divers. Distrib.* **2013**, *19*, 1208–1216. [CrossRef]
24. Haack, R.A. Exotic bark- and wood-boring Coleoptera in the United States: Recent establishments and interceptions. *Can. J. For. Res.* **2006**, *36*, 269–288. [CrossRef]
25. Liebhold, A.M. Forest pest management in a changing world. *Int. J. Pest Manag.* **2012**, *58*, 289–295. [CrossRef]
26. Herms, D.A.; McCullough, D.G. Emerald ash borer invasion of North America: History, biology, ecology, impacts, and management. *Annu. Rev. Entomol.* **2014**, *59*, 13–30. [CrossRef] [PubMed]
27. Sharov, A.A.; Leonard, D.S.; Liebhold, A.M.; Roberts, E.A.; Dickerson, W. "Slow the Spread": A national program to contain the gypsy moth. *J. For.* **2002**, *100*, 30–35.
28. Orwig, D.A.; Foster, D.R.; Mausel, D.L. Landscape patterns of hemlock decline in New England due to the introduced hemlock woolly adelgid. *J. Biogeogr.* **2002**, *29*, 1475–1487. [CrossRef]
29. Dajoz, R. *Insects and Forests*; Intercept LTD: Paris, France, 2000.
30. Knight, F.B.; Heikkenen, H.J. *Principles of Forest Entomology*, 5th ed.; McGraw-Hill, Inc.: New York, NY, USA, 1980.
31. Price, P.W.; Denno, R.F.; Eubanks, M.D.; Finke, D.L.; Kaplan, I. *Insect Ecology: Behavior, Populations and Communities*; Cambridge University Press: New York, NY, USA, 2011.
32. McManus, M.; Schneeberger, N.; Reardon, R.; Mason, G. Forest Insect and Disease Leaflet 162: Gypsy Moth. Available online: http://na.fs.fed.us/spfo/pubs/fidls/gypsymoth/gypsy.htm (accessed on 3 May 2016).
33. Fierke, M.; Nowak, D.; Hofstetter, R. Seeing the forest for the trees: Forest health monitoring. In *Forest Health: An Integrated Perspective*; Castello, J.D., Teale, S.A., Eds.; Cambridge University Press: New York, NY, USA, 2011; pp. 321–343.
34. USDA Forest Service. Early Detection Rapid Response Database (EDRR). USDA Forest Service, Forest Health Protection, 2016. Available online: http://foresthealth.fs.usda.gov/EDRR/ (accessed on 23 April 2016).
35. Tobin, P.C.; Kean, J.M.; Suckling, D.M.; McCullough, D.G.; Herms, D.A.; Stringer, L.D. Determinants of successful arthropod eradication programs. *Biol. Invasions* **2014**, *16*, 401–414. [CrossRef]
36. Pluess, T.; Cannon, R.; Jarošík, V.; Pergl, J.; Pyšek, P.; Bacher, S. When are eradication campaigns successful? A test of common assumptions. *Biol. Invasions* **2012**, *14*, 1365–1378. [CrossRef]
37. Suckling, D.M.; Stringer, L.D.; Stephens, A.E.A.; Woods, B.; Williams, D.G.; Baker, G.; El-Sayed, A.M. From integrated pest management to integrated pest eradication: Technologies and future needs. *Pest Manag. Sci.* **2014**, *70*, 179–189. [CrossRef] [PubMed]
38. Brockerhoff, E.G.; Liebhold, A.M.; Jactel, H. The ecology of forest insect invasions and advances in their management. *Can. J. For. Res.* **2006**, *36*, 263–268. [CrossRef]
39. Rassati, D.; Faccoli, M.; Marini, L.; Haack, R.A.; Battisti, A.; Petrucco Toffolo, E. Exploring the role of wood waste landfills in early detection of non-native wood-boring beetles. *J. Pest Sci.* **2014**, *88*, 563–572. [CrossRef]
40. Siegert, N.W.; McCullough, D.G.; Liebhold, A.M.; Telewski, F.W. Dendrochronological reconstruction of the epicentre and early spread of emerald ash borer in North America. *Divers. Distrib.* **2014**, *20*, 847–858. [CrossRef]
41. Muzika, R.M.; Liebhold, A.M. Changes in radial increment of host and nonhost tree species with gypsy moth defoliation. *Can. J. For. Res.* **1999**, *29*, 1365–1373. [CrossRef]
42. Naidoo, R.; Lechowicz, M.J. Effects on gypsy moth on radial growth of deciduous trees. *For. Sci.* **2001**, *47*, 338–348.
43. Rentch, J.; Fajvan, M.A.; Evans, R.A.; Onken, B. Using dendrochronology to model hemlock woolly adelgid effects on eastern hemlock growth and vulnerability. *Biol. Invasions* **2009**, *11*, 551–563. [CrossRef]

44. Sankaran, S.; Mishra, A.; Ehsani, R.; Davis, C. A review of advanced techniques for detecting plant diseases. *Comput. Electron. Agric.* **2010**, *72*, 1–13. [CrossRef]
45. Pontius, J.; Martin, M.; Plourde, L.; Hallett, R. Ash decline assessment in emerald ash borer-infested regions: A test of tree-level, hyperspectral technologies. *Remote Sens. Environ.* **2008**, *112*, 2665–2676. [CrossRef]
46. Chen, Y.; Whitehill, J.G.A.; Bonello, P.; Poland, T.M. Feeding by emerald ash borer larvae induces systemic changes in black ash foliar chemistry. *Phytochemistry* **2011**, *72*, 1990–1998. [CrossRef] [PubMed]
47. Speer, J.H. *Fundamentals of Tree-Ring Research*; The University of Arizona Press: Tucscon, AZ, USA, 2010.
48. Zhang, Q.; Alfaro, R.I.; Hebda, R.J. Dendroecological studies of tree growth, climate and spruce beetle outbreaks in Central British Columbia, Canada. *For. Ecol. Manag.* **1999**, *121*, 215–225. [CrossRef]
49. Chhin, S. Influence of Climate on the Growth of Hybrid Poplar in Michigan. *Forests* **2010**, *1*, 209–229. [CrossRef]
50. Fritts, H.C. *Tree Rings and Climate*; The Blackburn Press: Caldwell, NJ, USA, 1976.
51. Fritts, H.C. Dendroclimatology and dendroecology. *Quat. Res.* **1971**, *1*, 419–449. [CrossRef]
52. Sheppard, P.R. Dendroclimatology: Extracting climate from trees. *Wiley Interdiscip. Rev. Clim. Chang.* **2010**, *1*, 343–352. [CrossRef]
53. Briffa, K.R.; Schweingruber, F.H.; Jones, P.D.; Osborn, T.J.; Shiyatov, S.G.; Vaganov, E.A. Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature* **1998**, *391*, 678–682. [CrossRef]
54. Taylor, S.W.; Carroll, A.L.; Alfaro, R.I.; Safranyik, L. Forest, climate, and mountain pine beetle outbreak dynamics in western Canada. In *The Mountain Pine Beetle: A Synthesis of Biology, Management and Impacts on Lodgepole Pine*; Safranyik, L., Wilson, B., Eds.; Canadian Forest Service, Pacific Forestry Center: Victoria, BC, Canada, 2006; pp. 67–94.
55. Mbow, C.; Chhin, S.; Sambou, B.; Skole, D. Potential of dendrochronology to assess annual rates of biomass productivity in savanna trees of West Africa. *Dendrochronologia* **2013**, *31*, 41–51. [CrossRef]
56. David, E.; Chhin, S.; Skole, D. Dendrochronological potential and productivity of tropical tree species in Western Kenya. *Tree Ring Res.* **2014**, *70*, 119–135. [CrossRef]
57. Bokobza, L. Origin of near-infrared absorption bands. In *Near-Infrared Spectroscopy: Principles, Instruments, Applications*; Siesler, H.W., Ozaki, Y., Kawata, S., Heise, H.M., Eds.; Wiley-VCH: Weinheim, Germany, 2002; pp. 11–41.
58. Workman, J.; Shenk, J. Understanding and using the near-infrared spectrum as an analytical method. In *Near-Infrared Spectroscopy in Agriculture*; Roberts, C.A., Workman, J., Reeves, J.B., III, Eds.; Agronomy, American Societies of Agronomy, Crop and Soil Science: Madison, WI, USA, 2004; volume 44, pp. 3–10.
59. Schwanninger, M.; Rodrigues, J.C.; Fackler, K. A review of band assignments in near infrared spectra of wood and wood components. *J. Near Infrared Spectrosc.* **2011**, *19*, 287–308. [CrossRef]
60. Kramer, R.; Workman, J.; Reeves, J.B., III. Qualitative analysis. In *Near-Infrared Spectroscopy in Agriculture*; Roberts, C.A., Workman, J., Reeves, J.B., III, Eds.; Agronomy, American Societies of Agronomy, Crop and Soil Science: Madison, WI, USA, 2004; volume 44, pp. 175–206.
61. Ertlen, D.; Schwartz, D.; Trautmann, M.; Webster, R.; Brunet, D. Discriminating between organic matter in soil from grass and forest by near-infrared spectroscopy. *Eur. J. Soil Sci.* **2010**, *61*, 207–216. [CrossRef]
62. Evans, P.; Heady, R.; Cunningham, R. Identification of yellow stringybark (*Eucalyptus muelleriana*) and silvertop ash (*E. sieberi*) wood is improved by canonical variate analysis of ray anatomy. *Aust. For.* **2008**, *71*, 94–99. [CrossRef]
63. Watanabe, K.; Mansfield, S.D.; Avramidis, S. Wet-pocket classification in *Abies lasiocarpa* using spectroscopy in the visible and near infrared range. *Eur. J. Wood Wood Prod.* **2010**, *70*, 61–67. [CrossRef]
64. So, C.-L.; Via, B.K.; Groom, L.H.; Schimleck, L.R.; Shupe, T.F.; Kelley, S.S.; Rials, T.G. Near infrared spectroscopy in the forest products industry. *For. Prod. J.* **2004**, *54*, 6–16.
65. Schimleck, L.R. Near-infrared spectroscopy: A rapid non-destructive method for measuring wood properties, and its application to tree breeding. *N. Z. J. For. Sci.* **2008**, *38*, 14–35.
66. Schimleck, L.R.; Evans, R.; Ilic, J.; Matheson, A.C. Estimation of wood stiffness of increment cores by near-infrared spectroscopy. *Can. J. For. Res.* **2002**, *32*, 129–135. [CrossRef]
67. Riggins, J.J.; Defibaugh, J.M.; Tullis, J.A.; Stephen, F.M. Spectral identification of previsual northern red oak (*Quercus rubra* L.) foliar symptoms related to oak decline and red oak borer (Coleoptera: Cerambycidae) attack. *South. J. Appl. For.* **2011**, *35*, 18–25.

68. Fackler, K.; Schwanninger, M. How spectroscopy and microspectroscopy of degraded wood contribute to understand fungal wood decay. *Appl. Microbiol. Biotechnol.* **2012**, *96*, 587–599. [CrossRef] [PubMed]
69. Pontius, J.; Hallett, R.; Martin, M. Assessing hemlock decline using visible and near-infrared spectroscopy: Indices comparison and algorithm development. *Appl. Spectrosc.* **2005**, *59*, 836–843. [CrossRef] [PubMed]
70. Fackler, K.; Schwanninger, M.; Gradinger, C.; Srebotnik, E.; Hinterstoisser, B.; Messner, K. Fungal decay of spruce and beech wood assessed by near-infrared spectroscopy in combination with uni- and multivariate data analysis. *Holzforschung* **2007**, *61*, 680–687. [CrossRef]
71. Green, B.; Jones, P.; Nicholas, D. Assessment of the early signs of decay of *Populus deltoides* wafers exposed to *Trametes versicolor* by near infrared spectroscopy. *Holzforschung* **2012**, *66*, 515–520. [CrossRef]
72. Uto, K.; Seki, H.; Saito, G.; Kosugi, Y.; Komatsu, T. Development of a low-cost, lightweight hyperspectral imaging system based on a polygon mirror and compact spectrometers. *IEEE J. Sel. Top. App. Earth Obs. Remote Sens.* **2016**, *9*, 861–875. [CrossRef]
73. Eastman, J.R.; Zhu, H.; Lazar, A.; Williams, D.W. Progress on Remote Sensing Applications for Emerald Ash Borer Survey: Analysis of 2004 Hyperspectral Imagery. In Proceedings of the Emerald Ash Borer Research and Technology Development Meeting, Pittsburgh, PA, USA, 26–27 September 2005; pp. 66–67.
74. Hallett, R.; Pontius, J.; Martin, M.; Plourde, L. The Practical Utility of Hyperspectral Remote Sensing for Early Detection of Emerald Ash Borer. In Proceedings of the Emerald Ash Borer Research and Development Review Meeting, Pittsburg, PA, USA, 23–24 October 2007; pp. 67–68.
75. Bartels, D.; Williams, D.; Ellenwood, J.; Sapio, F. Accuracy Assessment of Remote Sensing Imagery for Mapping Hardwood Trees and Stressed Ash Trees. In Proceedings of the Emerald Ash Borer Research and Development Review Meeting, Pittsburg, PA, USA, 23–24 October 2007; pp. 63–65.
76. Zhang, K.; Hu, B.; Robinson, J. Early detection of emerald ash borer infestation using multisourced data: A case study in the town of Oakville, Ontario, Canada. *J. Appl. Remote Sens.* **2014**, *8*. [CrossRef]
77. Anulewicz, A.C.; McCullough, D.G.; Cappaert, D.L.; Poland, T.M. Host range of the emerald ash borer (*Agrilus planipennis* Fairmaire) (Coleoptera: Buprestidae) in North America: Results of multiple-choice field experiments. *Environ. Entomol.* **2008**, *37*, 230–241. [CrossRef]
78. Ryall, K. Detection and sampling of emerald ash borer (Coleoptera: Buprestidae) infestations. *Can. Entomol.* **2015**, *147*, 290–299. [CrossRef]
79. Tluczek, A.R.; McCullough, D.G.; Poland, T.M. Influence of host stress on emerald ash borer (Coleoptera: Buprestidae) adult density, development, and distribution in *Fraxinus pennsylvanica* trees. *Environ. Entomol.* **2011**, *40*, 357–366. [CrossRef]
80. Poland, T.M.; Chen, Y.; Koch, J.; Pureswaran, D. Review of the emerald ash borer (Coleoptera: Buprestidae), life history, mating behaviours, host plant selection, and host resistance. *Can. Entomol.* **2015**, *147*, 252–262. [CrossRef]
81. Cappaert, D.; McCullough, D.G.; Poland, T.M.; Siegert, N.W. Emerald ash borer in North America: A research and regulatory challenge. *Am. Entomol.* **2005**, *51*, 152–165. [CrossRef]
82. MacFarlane, D.W.; Meyer, S.P. Characteristics and distribution of potential ash tree hosts for emerald ash borer. *For. Ecol. Manag.* **2005**, *213*, 15–24. [CrossRef]
83. DeSantis, R.D.; Moser, W.K.; Gormanson, D.D.; Bartlett, M.G.; Vermunt, B. Effects of climate on emerald ash borer mortality and the potential for ash survival in North America. *Agric. For. Meteorol.* **2013**, *178–179*, 120–128. [CrossRef]
84. Tanis, S.R.; McCullough, D.G. Differential persistence of blue ash and white ash following emerald ash borer invasion. *Can. J. For. Res.* **2012**, *42*, 1542–1550. [CrossRef]
85. Pureswaran, D.S.; Poland, T.M. Host selection and feeding preference of *Agrilus planipennis* (Coleoptera: Buprestidae) on ash (*Fraxinus* spp.). *Environ. Entomol.* **2009**, *38*, 757–765. [CrossRef] [PubMed]
86. McCullough, D.G.; Poland, T.M.; Anulewicz, A.C.; Cappaert, D. Emerald ash borer (Coleoptera: Buprestidae) attraction to stressed or baited ash trees. *Environ. Entomol.* **2009**, *38*, 1668–1679. [CrossRef] [PubMed]
87. McCullough, D.G.; Poland, T.M.; Cappaert, D. Attraction of the emerald ash borer to ash trees stressed by girdling, herbicide treatment, or wounding. *Can. J. For. Res.* **2009**, *39*, 1331–1345. [CrossRef]
88. Crook, D.J.; Francese, J.A.; Rietz, M.L.; Lance, D.R.; Hull-Sanders, H.M.; Mastro, V.C.; Silk, P.J.; Ryall, K.L. Improving detection tools for emerald ash borer (Coleoptera: Buprestidae): Comparison of multifunnel traps, prism traps, and lure types at varying population densities. *J. Econ. Entomol.* **2014**, *107*, 1496–1501. [CrossRef] [PubMed]

89. Crook, D.J.; Khrimian, A.; Francese, J.A.; Fraser, I.; Poland, T.M.; Sawyer, A.J.; Mastro, V.C. Development of a host-based semiochemical lure for trapping emerald ash borer *Agrilus planipennis* (Coleoptera: Buprestidae). *Environ. Entomol.* **2008**, *37*, 356–365. [CrossRef]
90. Crook, D.J.; Mastro, V.C. Chemical Ecology of the Emerald Ash Borer *Agrilus planipennis*. *J. Chem. Ecol.* **2010**, *36*, 101–112. [CrossRef] [PubMed]
91. Grant, G.G.; Ryall, K.L.; Lyons, D.B.; Abou-Zaid, M.M. Differential response of male and female emerald ash borers (Col., Buprestidae) to (Z)-3-hexenol and manuka oil. *J. Appl. Entomol.* **2010**, *134*, 26–33. [CrossRef]
92. Domingue, M.J.; Lelito, J.P.; Fraser, I.; Mastro, V.C.; Tumlinson, J.H.; Baker, T.C. Visual and chemical cues affecting the detection rate of the emerald ash borer in sticky traps. *J. Appl. Entomol.* **2013**, *137*, 77–87. [CrossRef]
93. Silk, P.J.; Ryall, K.; Barry Lyons, D.; Sweeney, J.; Wu, J. A contact sex pheromone component of the emerald ash borer *Agrilus planipennis* Fairmaire (Coleoptera: Buprestidae). *Naturwissenschaften* **2009**, *96*, 601–608. [CrossRef] [PubMed]
94. Silk, P.J.; Ryall, K.; Mayo, P.; MaGee, D.I.; Leclair, G.; Fidgen, J.; Lavallee, R.; Price, J.; McConaghy, J. A biologically active analog of the sex pheromone of the emerald ash borer, *Agrilus planipennis*. *J. Chem. Ecol.* **2015**, *41*, 294–302. [CrossRef] [PubMed]
95. McCullough, D.G.; Siegert, N.W.; Poland, T.M.; Pierce, S.J.; Ahn, S.Z. Effects of trap type, placement and ash distribution on emerald ash borer captures in a low density site. *Environ. Entomol.* **2011**, *40*, 1239–1252. [CrossRef] [PubMed]
96. McCullough, D.G.; Siegert, N.W. Using Girdled Trap Trees Effectively for Emerald Ash Borer Detection, Delimitation and Survey. Available online: https://www.na.fs.fed.us/fhp/eab/survey/eab_handout.pdf (accessed on 3 May 2016).
97. Francese, J.A.; Oliver, J.B.; Fraser, I.; Lance, D.R.; Youssef, N.; Sawyer, A.J.; Mastro, V.C. Influence of trap placement and design on capture of the emerald ash borer (Coleoptera: Buprestidae). *J. Econ. Entom.* **2008**, *101*, 1831–1837. [CrossRef] [PubMed]
98. Poland, T.M.; McCullough, D.G.; Anulewicz, A.C. Evaluation of double-decker traps for emerald ash borer (Coleoptera: Buprestidae). *J. Econ. Entomol.* **2011**, *104*, 517–531. [CrossRef] [PubMed]
99. Francese, J.A.; Rietz, M.L.; Crook, D.J.; Fraser, I.; Lance, D.R.; Mastro, V.C. Improving detection tools for the emerald ash borer (Coleoptera: Buprestidae): Comparison of prism and multifunnel traps at varying population densities. *J. Econ. Entomol.* **2013**, *106*, 2407–2414. [CrossRef] [PubMed]
100. McCullough, D.G.; Mercader, R.J. Evaluation of potential strategies to SLow Ash Mortality (SLAM) caused by emerald ash borer (*Agrilus planipennis*): SLAM in an urban forest. *Int. J. Pest Manag.* **2012**, *58*, 9–23. [CrossRef]
101. United States Department of Agriculture, Animal and Plant Health Inspection Service, Plant Protection and Quarantine (USDA APHIS PPQ). USDA APHIS PPQ: 2015 Emerald Ash Borer Survey Guidelines. Available online: https://www.aphis.usda.gov/plant_health/plant_pest_info/emerald_ash_b/downloads/survey_guidelines.pdf (accessed on 3 May 2016).
102. Mercader, R.J.; McCullough, D.G.; Bedford, J.M. A comparison of girdled ash detection trees and baited artificial traps for *Agrilus planipennis* (Coleoptera: Buprestidae) detection. *Environ. Entomol.* **2013**, *42*, 1027–1039. [CrossRef] [PubMed]
103. Ryall, K.L.; Fidgen, J.G.; Turgeon, J.J. Detectability of the emerald ash borer (Coleoptera: Buprestidae) in asymptomatic urban trees by using branch samples. *Environ. Entomol.* **2011**, *40*, 679–688. [CrossRef] [PubMed]
104. Herms, D.; McCullough, D.G.; Smitley, D.R.; Clifford, C.S.; Cranshaw, W. *Insecticide Options for Protecting Ash Trees from Emerald Ash Borer Insecticide*, 2nd ed.; North Central IPM Center: USA, 2014; pp. 1–16.
105. USDA-APHIS/ARS/FS. *Emerald Ash Borer, Agrilus planipennis (Fairmaire), Biological Control Release and Recovery Guidelines*; USDA-APHIS-ARS-FS: Riverdale, MD, USA, 2012.