Title: *Quantifying firewood-transmitted forest pests at their source: an analysis of insects within a Northern Colorado firewood processing facility.*

Authors and Committee

*Garron Snyder, Fish and Wildlife Conservation Biology (Major) and Restoration Ecology (Minor), Colorado State University, Fort Collins, CO. 835-448-755. Expected May 2025. Contact: garron.snyder@colostate.edu. Author**

*Seth Davis, Associate Professor of Forestry, Colorado State University, Fort Collins, CO. Contact: seth.davis@colostate.edu. Thesis Advisor**

*Crystal Cooke. Entomology Instructor and Curator at CP Gillette Museum of Arthropod Diversity, Colorado State University, Fort Collins, CO. Contact: crystal.cooke@colostate.edu Thesis Committee Member**

Figure 1. Image of Scolytus schevyrewi (left) and its associated galleries on an elm log (right). Photos taken during sampling.

Abstract: Urban and rural forests are subject to outbreaks from forest pests of native and foreign origin. Firewood is one of the primary dispersal agents of forest pests such as insects, bacteria, and fungi. However, few studies have attempted to quantify pest incidence within transported firewood. This study analyzed forest pest incidence within a firewood processing and holding facility in Northern Colorado by quantifying the proportions of pieces with galleries, live adult insects, dead adult insects, and larvae within imported and locally processed firewood. We also analyzed locally felled tree species for galleries, and adult or larvae species richness to investigate local incidence. Lastly, we utilized funnel traps baited with α-pinene-ethanol baits to capture and identify any species present within the property. Among the 3,250 pieces of firewood, 28% (925) contained galleries, less than 1% (12) had live insects, and zero contained larvae. The largest average proportion of galleries was observed in pine pallets (81% per pallet) and the smallest was observed in spruce (0.05% per pallet). In sampled logs, elm logs had the highest gallery incidence (90%), alive adult presence (80%), larvae presence (90%), and species richness. A variety of native, but potentially harmful pests were captured along with evidence of potentially harmful insects such as members of Buprestidiae, Cerambycidae, and Curculionidae. Based on our analysis, we suspect that the firewood tree species is an important factor to consider when quantifying and predicting forest pest dispersal. We also believe that local firewood is not inherently less likely to harbor potentially harmful species compared to imported firewood. Overall, better monitoring and regulatory structure will be necessary to prevent forest pest outbreaks.

Keywords: *Firewood, Forest Pests, Urban Forests, Emerald Ash Borer, Asia Longhorn Beetle, Mountain Pine Beetle, Northern Colorado, Thousand Cankers Disease, Dutch Elm Disease*

1. Introduction

1.1 Impacts of Commercial Firewood Sales

Humans have harvested, burned, and moved firewood for centuries. Today, it is still widely utilized for residential heating, recreation, and restaurant use in the United States. Recent surveys suggest that 47% of residents in the United States still use firewood for recreation or as a heat source (Solano et al. 2020). However, commercial firewood consumption has had unintended effects on the health of the nation's urban and rural forests. Firewood is one of the primary vectors of transmission for insects, fungi, bacteria, oomycetes, and non-native plant propagules collectively referred to as forest pests (Boyd et al. 2013; Eigenbrode et al. 2018; Solano et al. 2020; Tobin et al. 2010). The economic impact of forest pests ranges from 1 million to 14.4 billion USD per year from lost or decreased yield in wood products, property values, ecosystem services, food crops, and other important tree-mediated processes (Boyd et al. 2013; Solano et al. 2020). Firewood sales are largely unmonitored compared to other commercial exports and imports (Diss-Torrance et al. 2018). As such, many urban and natural forests are at risk from new outbreaks of non-native species and increased dispersal of native pests.

Forest pest dispersal has caused large-scale damage to both urban and natural forests. Notable examples include the spread of *Lymantrua dspar dispar* (spongy moth) which has caused the defoliation of 30 million ha of forests between the United States and Canada (Hussain et al. 2024). Early season defoliation has been estimated to decrease gross ecosystem productivity by 459 g C /m^2 per year in eastern states with high spongy moth incidence (Latifovic et al. 2024). *Anoplophora glabripennis* (Asian longhorned beetle) is responsible for 1.5 billion USD in damages in China alone. EAB has inflected similar damage in the U.S. since its initial infestation in New York in 1996 (Hu et al. 2009). The continued spread of *Agrilus panipennis* (emerald ash borer or "EAB") is projected to cost 10.7 billion USD in damage to the 37.8 million ash trees present in urban forests, private property, and riparian corridors (Kovacs et al. 2010). Although EAB may have originated from timber products, many satellite infestations have arisen through firewood dispersal (Kovacs et al. 2010; Solano et al. 2020; Tobin et al. 2010). Nationwide, many trees are already drought-stressed, burdened by pathogens, or threatened by changing fire regimes and climate conditions (Eigenbrode et al. 2018, Esperon-Rodriguez et al. 2022). The continued spread of forest pests has the potential to increase disturbance-pressure in forests and disrupt critical ecological processes such as carbon sequestration, oxygen production, water storage, disease regulation, and increase the cost of management/mitigation strategies (Alexander et al. 2019; Tobin et al. 2010; Jentch et al. 2020).

1.2 Firewood Pest Ecology

Forest pests are often categorized by their origin and mode of harm. Non-native insects and pathogens are often introduced into areas far outside of their natural range; primarily through anthropogenic routes such as wood products, food, and transportation vehicles. (Hu et al. 2009; Tobin et al. 2010). Examples include EAB, spongy moth, and the Asian longhorned beetle. All of which likely originated from Asian countries through imported wood products (Hu et al. 2009). Native pests are insects and pathogens that are present in a system via natural distributions but may have harmful impacts on tree health. Many native pests already exist in Colorado, including members of bark beetles (family Curculionidae), clearwing borers (family Sesiidae), longhorned beetles (family Cerambycidae), and metallic wood borers (family Buprestidae). One of the most significant species is *Dendroctonus ponderosae* (Mountain pine beetle) which has caused tree mortality in 3.9 million acres of forest since an increase in outbreaks in the 1990s (Negron & Cain 2019). Many of these species have spread at a rate that exceeds their natural dispersal which has potentially impacted fire regimes, pollination patterns, carbon sequestration, and other ecological processes (Costelo et al. 2013; Negron & Cain 2019; Porunou 2020). Although both groups can harm natural and urban forests, introduced species have a competitive advantage as they are often free of pressure from their natural predators. This is the case for the Asian lognhorned beetle, which is free of natural predators in the North American continent (Hu et. al 2009). Many native pests can exist in populations that are not necessarily harmful due to limiting abiotic factors (tree susceptibility, seasonal climate patterns, spatial distribution, etc.) and biotic factors (natural predators, competing species, etc.). However, moving either of these groups can potentially lead to outbreaks, given that the conditions of the infestation site promote population growth and release them from their previous pressures.

Forest pests can directly harm trees and other plants through defoliation and wood-boring (Boyd et al. 2013; Pournou 2020). The insect orders Coleoptera (beetles), Blattodea (termites), Hymenoptera (ants, bees, wasps), and Lepidoptera (moths and butterflies) host the largest number of wood-boring or defoliating members (Pournou 2020). Many species in these orders are either xylophagous (they consume the xylem tissue from a tree) or phyllophagous (they consume inner bark tissue layers or cambium tissue) (Porunou 2020). Other species may create or utilize pre-existing tunnels (galleries) to complete their reproductive cycle (i.e., members of subclade Aculeta)(Westerfelt 2015). The resulting tunnels from woodborers are reliable signs of previous incidence and are often used to identify pests due to the unique gallery patterns produced by specific species. Woodboring activity damages critical tree tissue that moves nutrients and water throughout the plant and protects it from natural disturbances such as fire and pathogens. The level of incidence (galleries, live adults, larvae) is an important factor. For example, ash trees often do not show signs of distress (thinning canopies, dead branches, and basal shoots) until the 3rd or 4th year of infestation as it takes time for the EAB population to increase to a critical point that causes significant harm to the tree (City of Fort Collins 2020; Kovacs et al. 2010).

Forest pests can indirectly harm trees by introducing pathogens or reducing the trees' ability to withstand infection (Agrios et al. 2008; Boyd et al. 2021; Eigenbrode et al. 2018; Marchetti et al. 2011). Many pests can contribute to direct or additive mortality in trees already burdened by drought, disease, or other infestations (Marchetti et al. 2011). Insects can vector 30-40% of tree diseases through direct contact or by facilitating the microhabitat needed for the disease to colonize (Agrios et al. 2008). For example, Thousand Cankers Disease (TCD) is a tree disease that is caused by the fungus *Geosmithia morbida,* which grows inside of abandoned insect galleries (Gazis et al. 2018; Tisserat et al. 2011). Dutch elm disease (DED) is another fungal tree infection caused by *Ophistoma ulmi* that spreads through bark beetles, particularly *Hylurgopinus rufipes* (Hubbes 1999). From 1930 to 1976, 56% of urban elm trees had been infected or lost due to the rapid spread of DED (Agrios et al. 2008; Hubbes 1999). Insects can create dormant disease pools that are hard to manage. Overwintering or dormant insects can harbor bacterial and fungal spores that can be reintroduced into the environment once they emerge (Agrios et. al 2011). Colonization can increase the virulence of pathogens by spreading disease throughout an individual tree at a rate that exceeds natural spread (Agrios et al. 2008; Gazis et al. 2018).

1.3 Local Events and Research Gaps

Human activity has increased the spread of forest pests and pathogens within urban and rural forests in Colorado. Native species such as the mountain pine beetle, *Dryocoetes confuses* (balsam bark beetle), and *Dendroctonus rufipennis* (spruce beetle) continue to spread through Colorado's rural and urban forests at unprecedented rates (Derderian et al. 2016; Marchetti et al. 2011; Negron & Cain 2019).

Additionally, non-native invasive outbreaks are continuing to spread throughout the state. In 2013, the EAB first appeared in Boulder County, prompting a federally mandated quarantine of wood products until its dissolution in 2019 (Alexander et al. 2019; City of Fort Collins 2020). In 2020, the EAB was confirmed in Fort Collins, prompting immediate insecticide treatments given the city's population of 70,000 ash trees worth approximately 1.3 million USD (City of Fort Collins 2020). Since the initial outbreak, satellite infestations have spread throughout Larimer County and Adams County, Colorado (City of Fort Collins 2020).

Currently, the direct pathways of these outbreaks are poorly understood. A metanalysis on the spread of invasive species in the United States identified a monitoring gap in the Western United States, particularly in Colorado (Solano et. al 2020). This study aimed to establish if forest pest incidence exists within a firewood processing facility in Northern Colorado. If so, we wished to investigate if the signs of incidence vary based on origin, vendor, or tree species. We also aim to identify any pest species present. Our study contributes to the growing literature on insect pest dispersal and helps close the current monitoring gap. Based on similar studies, we expected that imported firewood would have the highest proportion of incidence overall. We believed it was likely that the presence of larvae would be greatest in imported firewood due to the ability of insect larvae to remain in firewood months to years after infestation (Haack et. al 2010). We also expected that locally felled tree species would have low signs of incidence overall. However, spruce logs may have more signs of incidence given nearby spruce beetle infestations.

2. Methods

2.1 Sample Area

The firewood facility is a ~40-acre ranch in the Northern Colorado plains. The property is dominantly used for firewood production as well as cattle grazing and is located in a central commerce corridor. Dominant plant species include *Pascopyrum smithii* (western wheatgrass), *Agropyron cristatum* (crested wheatgrass), *Crysothamnus spp.* (rabbitbrush), and various agricultural weeds such as kochia and Russian thistle. The property can be classified by four distinct areas or "ecotones" (Figure 2). Ecotone 1 is a restored vegetation belt around the developed area of the property that consists of mostly replanted native grasses, shrubs, and a few ornamental trees. This area is not grazed, not used for wood production, and is mostly undisturbed. Ecotone 2 is the grazed pasture that comprise most of the land mass. Here, the vegetation is a mostly even mix of native grasses and agricultural weeds. Ecotone 3 is the developed wood processing portion of the property that is devoid of most vegetation and used to overwinter processed wood. Heavy machine disturbance and wind erosion is common in this area. Ecotone 4 is the manicured lawn that surrounds the main building and is a mix of ornamental or native vegetation.

2.2 Trap Samples

We investigated the presence of live forest pest insects using baited funnel traps. Data collected from this approach evaluated if decades of firewood processing had established populations of forest pests. Traps were baited with α-pinene-ethanol baits and paired with an insecticide strip. The attachment style varied based on tree availability within the sampled area; traps were either free-standing or tree-mounted. We deployed six traps using a random grid generator stratified by ecotone. Two traps were placed on opposite ends of the pasture (Ecotone 2), two in the different processing areas (Ecotone 3), one in the central holding area (Ecotone 3), and one in the yard (Ecotone 4) (see figure 1). Each trap was given a unique ID: Pine Processing North (PPN), Pine Processing South (PPS), Holding Central (HC), Pasture West (PW), Pasture East (PE), and Yard (Y). Trapping began mid-September and ended in late October. Traps were emptied once a week and insects were identified to a family or genus level (Pournou 2020).

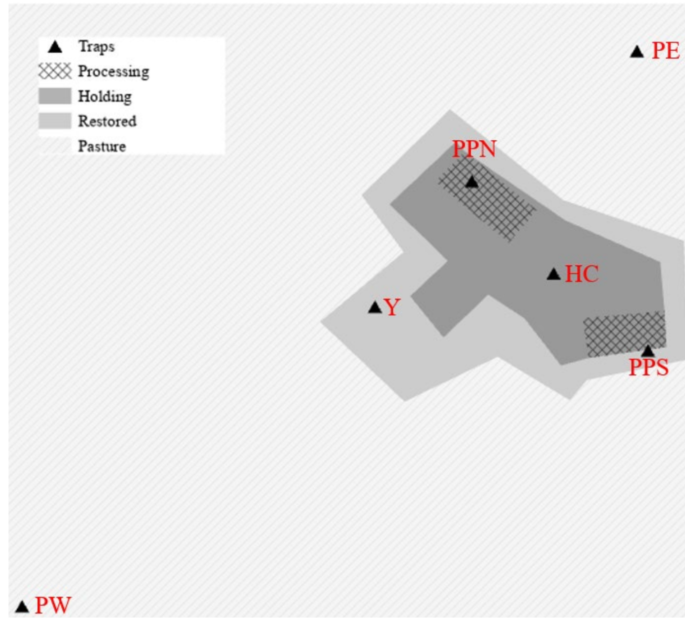

Figure 2. Outline of study area. Traps are labled as follows: Pasture East (PE), Pasture West (PW), Pine Processing North (PPN), Pine Processing South (PPS), Holding Central (HC), and Yard (Y)

2.3 Log Samples

We estimated incidence and species richness within local firewood by screening recently felled, local tree species prior to processing. During the sampling period, only three species of local trees were available: *Picea pungens* (blue spruce), *Ulmus sp.* (elm), and *Elaeagnus angustifolia* (Russian olive). 10 whole logs for each species were screened for incidence. Sampled logs were examined using a “bio-blitz” style approach (Nicolai et al. 2020). Each log was sampled for 20 minutes. During the sampling interval, the bark was removed, and the number of unique adult and larvae species was recorded. Additionally, the presence of galleries, alive adult insects, dead adult insects, and larvae were recorded on a binary scale (present =1, absent = 0). Insects that flew onto the log during the observation period were not counted. Any insects noticed after the initial sampling period were also not included. Photo evidence of galleries were collected to identify the origin species of the gallery.

We first analyzed each tree species independently using a series of ANOVA tests evaluated by Akaike’s Information Criterion (AIC) to test if adult species richness and larvae species richness could be predicted by the category of incidence (Gotelli & Ellison 2004; Powel & Gale 2015). For example, in elm logs, a candidate model-set was built to analyze if the variation in adult richness could be explained by the presence or absence of adults, dead adults, larvae, or galleries using an ANOVA test. The best supported model based on the AICc value and model weight was selected out of this subset. A separate candidate model was built to predict larvae richness based on the same indices. This process was then repeated for each species to build a predictor table (table 4).

2.4 Pallet Samples

We screened processed firewood pallets to determine if incidence was more likely to occur based on origin (local or imported), tree species, or vendor. Locally processed firewood consisted of *Picea pungens* (blue spruce), *Pinus contorta* (Lodgepole pine), *Populus deltoides* (plains cottonwood), *Populus tremuloides* (quaking aspen), *Fraxinus sp.* (ash), and *Ulmus sp.* (elm). Imported firewood consisted of

Pinus edulis (Colorado pinon), *Quercus fusiformis* (Texas live oak), three variations of *Carya sp.* (pecan and hickory), *Prunus serotina* (black cherry), and *Prosopis sp.* (mesquite). We were unable to identify the exact species of some trees. However, for the scope of this study, the genus of each tree is adequate. In total, six species of local firewood and 6 species/vendors of imported firewood were sampled. Firewood either arrived processed or was later processed into 1.8 m^3 pallets. We screened each batch for live insects, galleries, larvae, and dead insects. For each batch, 10 pallets were randomly chosen and 25 pieces within those pallets were screened for insect incidence. The species, vendor, origin (local or imported), and proportion of each incidence group was recorded for each sampled pallet. We collected photo evidence for each unique gallery for later identification.

We analyzed the gallery data with an analysis of variance test (ANOVA) to determine if the proportions of each incidence indicator were greater within or between the groups (vendor, species, origin)(Gotelli & Ellison 2004; Powel & Gale 2015). For each pallet, we calculated the proportion of each incidence type (galleries, live adults, dead adults, and larvae). The proportion was recorded as the number of sampled pieces per pallet with incidence out of the 25 randomly selected pieces. The ANOVA test was completed using the set of hypotheses outlined in table 1. The competing models were then compared using Akaike's Information Criterion (AIC) to determine the most likely explanation for the variation of incidence (Gotelli & Ellison 2004; Powel & Gale 2015).

Hypothesis	Model
H_0	Proportion of (Incidence) ~ Equal
H_{a1}	Proportion of (Incidence) ~ Species
H_{a2}	Proportion of (Incidence) ~ Origin
H_{a3}	Proportion of (Incidence) ~ Vendor

Table 1: Model hypothesis for pallet data for ANOVA. The four hypotheses were completed for each type of incidence (galleries, live adults, dead adults, and larvae).

3. Results

3.1 Trap Data

Live insect traps revealed mostly native species of moths, spiders, flies, and aphids. However, 100% of the traps tested positive for *Scolytus schevyrewi* (red-banded elm bark beetle). The PPS, Y, and PE traps also collected specimens of *Sirex cyaneues* (blue horntail sawfly), a burrowing insect. Most specimens were damaged or predated during trapping which limited our sample size. Predatory beetles (non-borers) were ignored and only boring species were identified further.

3.2 Pallet Samples

In total, 130 pallets were sampled across 12 tree species and 7 vendors. 3,250 pieces of firewood were screened for signs of incidence. Of the 130 sampled pallets, 100% contained at least one sign of previous incidence (mostly bark and boring beetle galleries). Among the 3,250 total pieces of firewood, 28% (925) contained galleries, less than 1% (12) had live insects, and zero contained larvae. Due to the low levels of live adult and larvae incidence, these categories were not candidates for further analysis. The greatest number of live insects were found in local firewood (elm and lodgepole pine).

The overall average gallery incidence per pallet (figure 2, top) was 28% with the largest average observed in pine pallets (81% per pallet) and the smallest observed in spruce (0.05% per pallet). The variance and standard error for each species was small with a few outliers depicted in figure 2 by the black dots. The greatest variance was observed in pecan pallets. When stratified by origin, the imported pallets had an average gallery incidence of 22% while local firewood had an average of 36% (figure 3, middle). Local firewood had a larger variance (0.11) compared to imported firewood (0.03). In the imported pallets, the vendors JRP (Oklahoma pecan) and TCO (Texas live oak) had the largest average gallery incidence (51% and 41% respectively). SWH (Oklahoma Hickory) had the lowest level of gallery incidence (6%).

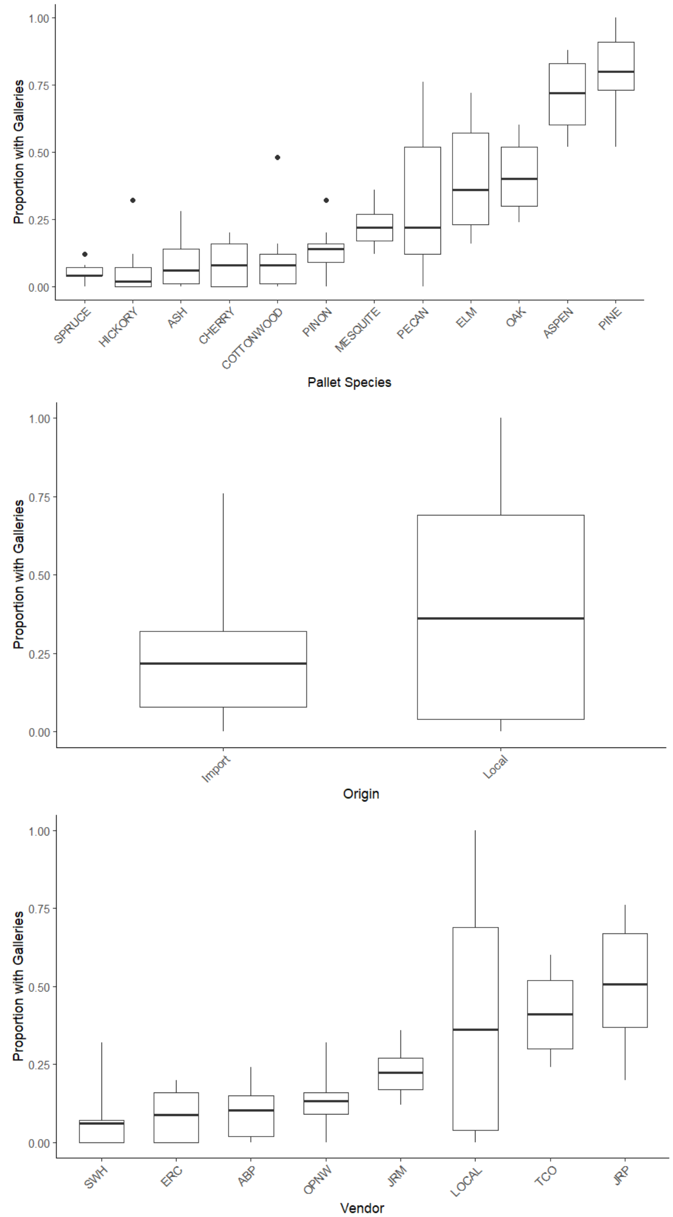

Figure 3. Top: Boxplot of average proportion per pallet of sampled pieces that contained boring beetle galleries. Black dots represent outliers. Middle: Boxplot of average proportion per pallet of sampled pieces stratified by origin (imported or local). Bottom: Proportion of sampled pieces with galleries stratified by vendor.

The AIC candidate model analysis revealed that it is likely the proportion of galleries may be dependent on the tree species rather than the vendor (table 2). The AICc model weight for this model was 100%. The ANOVA test produced an F-Statistic of 29.37 with an associated p-vale of 2.00E-16. It is important to note that during further analysis, the residuals of these models did not follow a normal distribution and error in our analysis may be possible.

Model	AICc	ΔAICc	AICcWt	LL	K	F-Stat	P-Value
Prop. Gal. ~ Species	-107.14	0	1	68.14	13	29.37	2.00E-16
Prop. Gal ~ Vendor	16.99	124.13	0	1.26	9	5.854	7.15E-06
Prop. Gal ~ Origin	32.32	139.46	0	-13.06	3	9.178	0.003
Null	29.23	146.37	0	-17.57	2		

Table 2. Akaike information criterion model selection table from ANOVA analysis of the proportion of galleries. LL represents the log likelihood of the model and K denotes the number of parameters used.

3.3 Log Samples

We sampled a total of 30 logs across 3 species of local trees including elm, spruce, and Russian olive (10 logs each). Elm logs had the highest gallery incidence (90%), alive adult presence (80%), and larvae presence (90%). Spruce logs had the lowest gallery incidence (40%) and alive adult presence (50%). The greatest average adult and larvae richness was observed in elm logs (2.7 and 1.7 respectively) as depicted in figure 3. The greatest larvae and adult richness were observed in elm logs.

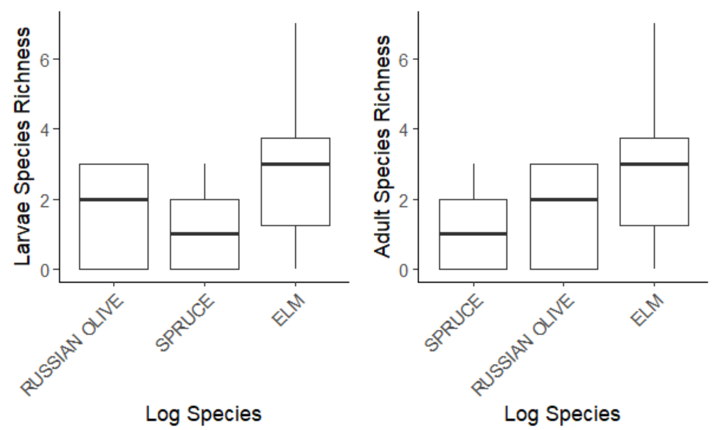

Figure 4. Boxplot depicting adult species richness and larvae species richness stratified by log species. Black bar represents mean. Boxes represent 2nd and 3rd quartiles.

The AIC candidate model tests suggest that the variability in larvae richness can be explained by the presence of galleries. This model had the highest F-statistic (8.02) with an associated p-value of 8.00E-03. This model is 7.3 times more likely than the "Larvae Richness ~ Alive Adults model" according to the AICc weights in column 4 of table 3. For adult richness, the presence of dead adults was the best predictor for adult richness. This model produced an F-Statistic of 6.394 with an associated p-value of 0.02. Note, the next best model (Adult Richness ~ Dead Adults) only has a delta AIC of 1.52 which suggests it is a possible candidate for explaining the variability in adult species richness.

<u>*Larvae Richness*</u>

Model	AICc	ΔAICc	AICcWt	LL	K	F-Stat	P-Value
Larvae Richness ~ Galleries	85.49	0.00	0.81	-39.32	3	8.02	8.00E-03
Larvae Richness ~ Alive Adults	89.60	4.07	0.11	-41.35	3	3.49	7.00E-02
Larvae Richness ~ Null	90.63	5.14	0.06	-43.11	2	-	-
Larvae Richness ~ Dead Adults	92.65	7.16	0.02	-42.9	3	0.397	0.53

<u>*Adult Richness*</u>

Model	AICc	ΔAICc	AICcWt	LL	K	F-Stat	P-Value
Adult Richness ~ Dead Adults	123.30	0.00	0.57	-58.22	3	6.394	0.02
Adult Richness ~ Larvae Presence	124.82	1.52	0.27	-58.98	3	4.703	0.038
Adult Richness ~ Null	127.04	3.74	0.09	-61.31	2	-	-
Adult Richness ~ Galleries	127.49	4.19	0.07	-60.32	3	1.925	0.176

Table 3. Akaike information criterion model summary generated from ANOVA analysis of larvae richness (top) and the analysis of adult richness (bottom) by presence of incidence (yes or no).

When stratified by tree species, the variability in adult and larvae richness was explained by different incidence types (table 4). For example, the presence of galleries had the greatest effect on the larvae species richness in elm logs. However, none of the incidence types had a significant effect on the adult species richness. As such, the null model was accepted. In Russian olive logs, the presence of dead adults had the greatest effect on the adult species richness. The larvae species richness analysis was nullified as zero larvae were found in Russian olive logs. In Spruce logs, the presence of larvae had the greatest effect on adult species richness while the null model was accepted for larvae species richness.

Species	Adult richness is predictable by…	Larvae richness is predictable by…
Elm	null	presence of galleries
Russian Olive	presence of dead adults	-
Spruce	presence of larvae	null

Table 4. Summary of candidate models effect size on adult and larvae species richness, stratified by tree species.

4. Discussion

Figure 1. Example galleries from processed and un-processed firewood. Top Left: Cambium remains from a bark beetle infestation on an elm log. Bottom Left: Pine beetle gallery found on a pine firewood piece Center: Wondering gallery indicative of a poplar wood borer (Saperda sp.) Right: Elm firewood piece gallery indicative of elm bark beetle Scolytus schevyrewi.

4.1 Key Findings

We aimed to monitor a firewood processing facility for signs of forest pest incidence and establish if these indices varied by origin, vendor, or tree species. In addition, we wished to establish if imported firewood was more likely to harbor forest pests than local firewood sources. From our traps, we attempted to identify any pest species present. We predicted that imported firewood would have the highest proportion of all incidence types. In locally felled trees, we expected to find low signs of incidence overall, but higher signs relatively in spruce species.

Our data revealed that there is evidence of previous infestations within processed firewood at a significant prevalence level. 100% of the 130 pallets screened showed at least one sign of prior incidence. It is important to consider potential dispersal at the pallet-level because firewood is sold by the pallet (1/2 cord). Our data suggests almost every pallet has the possibility to spread insects or pathogens given the evidence of prior infestation. On a more refined scale, 28% of the 3,250 sampled firewood pieces showed prior incidence. This observed value is comparable to similar studies. For example, Jacobi et al. sampled bundles of firewood and found that 50% contained signs of prior infestations (2011). Haack et al. sampled individual firewood pieces and observed 41% with prior incidence and 23% with live borer beetle species (2010). However, their study utilized a smaller sample size (1027). Our observations revealed only 1% (12) of our sampled pieces contained live insects and 0% contained larvae. The type of incidence most observed in our study were the tunnels/galleries of wood-boring and bark beetles.

Similarly, our study agrees with Haack et al. that all firewood tree species can vector forest pest species (2010). However, we observed a large variability in incidence rates of galleries between tree species. Our analysis revealed that the proportion of pieces with galleries varied by tree species ($F = 29.7$, $p = 2.00E-16$) rather than by vendor or origin. Note, the ANOVA tests revealed that vendor and origin were potentially significant covariates, but did not explain the variation in the data as well as the tree species model. Lodgepole pine and aspen tree species were the most likely to contain galleries which is consistent with sampling completed by Jacobi et al. (2011). *Pinus contorta* and *Populus tremuloides* populate many ha of nearby forests which suggests infestations may be present and possibly widespread in nearby forests. However, we can only confidently make this claim for *P. contorta* given that many aspen trees originated from local urban forests rather than natural forests. Similarly, all of the *Picea pungens* logs and pallets had the lowest rates of incidence, but all originated from local urban forests. Even though we cannot quantify infestations based on urban or natural forest origin, we still have evidence that infestations exist in both of these systems and can possibly be spread through firewood sales.

Our tree species analysis also revealed that certain species and vendors may be less likely to transport insects. For example, firewood tree species such as spruce (local), hickory (imported) and ash (local) may be relatively "safe" to use given their relatively lower proportions of incidence. It is difficult to make this claim with certainty given that some species (such as *Ips* beetles) do not survive well out of their native habitat while others have better chances of surviving long distance dispersals (i.e. Asian longhorn ed beetle). Additionally, some populations can rebound with only a few larvae while others require an already robust population to spread into a new system (Pournou 2020).

Although we did not find species of major concern, our results show that a few invasive insects may exist within the property. For example, *Sirex cyaneues* completes its lifecycle by burrowing into live trees to deposit larvae. Our records indicate that this species has not been described in Fort Collins. This may prompt further surveillance and sampling. *Scolytus schevyrewi* is likely a vector for DED and is the most probable culprit for the destruction of elm trees brought to the property. The galleries of this bark beetle were ubiquitous throughout our samples suggesting they have a high prevalence in the area.

One of the most important findings is that local firewood is not inherently less likely to spread forest pests as other studies suggest (Tobin et al. 2010). The average proportion of galleries between local and imported firewood was 22% and 36%, respectively. Our analysis suggests that although there is some variation present between the groups, it is not as significant as the variance between vendors and species ($F = 9.178$, $p = 0.003$). Locally sourced pallets contained samples with the highest proportion of galleries as well as the lowest. This suggests that local firewood is merely a conglomeration of local pest infestations (native and non-native). Although firewood is one of the most significant vectors of forest pests, it is not the only route of infestation (Jentsch et al. 2020). For example, EAB may have originated from ash lumber and then spread through firewood and other ash products (Kovacs et. al 2010). Additionally, firewood from other vendors, imported lumber, imported trees, and other plant products can vector native and non-native pests. Ultimately, our local samples reflect the current state of infestation for Northern Colorado's urban and natural forests.

Our local log samples illustrate the diversity of insects and potential pests present in just a few species of trees. Elm logs, a target of multiple forest pest species such as *Hylurgopinus rufipes* (elm bark beetle), had the highest species richness, frequency of galleries, and the most larvae present. It is possible that the infestation led to the tree's destruction either through damaged xylem and phloem tissue or through Dutch elm disease. In contrast, we would expect spruce logs to show the most incidence given nearby infestations of spruce beetles. However, most spruce logs originated from properties within city limits which suggests spruce beetle infestations are not currently prevalent in Fort Collins. Interestingly, larvae prevalence in whole logs did not directly translate to larvae prevalence in the processed pallets of the same tree species. Zero larvae were detected during pallet sampling. Given that larvae were identified in whole elm logs but not in processed pallets, it is possible that larvae are either destroyed during processing or emerge from pallets after the overwinter process of drying firewood prior to sale. Mechanical processes such as sawing and hydraulic splitting paired with overwintering may reduce larvae presence in firewood. However, this claim requires further research and would only be effective if emerged insects did not eventually bore into other firewood within the property.

The motivating argument for local firewood assumes that local firewood only harbors local species and is less damaging than imported firewood (Solano & Rodriguez 2020). This assumption is only viable in regions free of non-native pests or accelerated native pest outbreaks. Even if this criterion is met, it is still possible to accelerate insect and pathogen dispersal beyond a natural rate (Lantschner & Corley 2023). Additionally, public guidelines regarding firewood use rarely define "local" use. Burning an elm log from an urban forest in a *pinus ponderosa* forest system would not be inherently local even if the distance traveled is only a few km. Moving forward, better monitoring is required to establish current outbreaks and clearer guidelines for local firewood use are needed in order to ensure responsible firewood consumption.

4.2 Data Constraints and Lessons Learned

We cannot reliably quantify the probability of pest transfer given this data. Yet, we have evidence that local and imported firewood are likely to harbor forest pests. For our purposes, any signs of incidence are significant as they represent the possibility of forest pest transfer. Galleries alone do not immediately translate into a new pest outbreak. Rather, they inform us that potentially invasive species were once present in that firewood sample and most likely deposited larvae or pathogens within those galleries. Further investigation is required to confidently claim that firewood from our sample is likely to transport insects outside of their natural habitat dispersal range. Overall, we have to consider important constraints and limitations that may influence our predictions of how and why the incidence occurred. For example, the origin of the tree varies beyond our defined categories: local and imported. Sampled logs were mostly ornamental trees from private properties while pallet data included a mix of orchard, ornamental, and naturally occurring tree sources. It is possible that pest species incidence can further vary based on the specific origin type. This hypothesis was not explored in this study as we were unable to verify the specific origin type for each imported tree species.

The season of our study is also a possible influencing factor. Many wood-boring beetle species such as the Asian longhorned beetle reach peak emergence in June and begin to bore larvae deposits in late August (Lantschner et. al 2023). Other species such as the mountain pine beetle follow a similar pattern (Negron & Cain 2019). Our sample period took place in early to late fall (September through October). It is possible that over this time frame, insects may have bored into previously sampled logs and pallets. If this unknowingly took place, pallets and logs sampled later in the season may have inflated species richness and the number of adults present compared to those sampled earlier. Additionally, this study was completed within one season. Future studies should consider monitoring and sampling across several years or seasons to capture the larger network of pest transmission.

Other factors such as the independence of samples and moisture content may have introduced bias into the data. The goal of the study was to sample imported pallets as soon as they arrived and compare the data to local pallets as a control. However, imported pallets were not always sampled the same day as they arrived. It is possible that any insects present at the processing facility may have entered the recently imported pallets. The likelihood of cross-contamination increases if the imported wood was "green" (freshly cut). It is known that "green" firewood with high moisture content is more likely to harbor insects as the microenvironment is more favorable and larvae have yet to emerge (Pournou 2020; Solano et al. 2020). The moisture content of sampled firewood was not controlled in this study. Moisture and time since arrival would influence our estimate of adult/larvae richness and number of adults/larvae present but would likely have no effect on the estimate of wood-boring beetle gallery incidence. Wood galleries occur pre-emergence and are present long after the adult/larvae have left the sample. As such, the gallery data was used as our primary estimator of incidence.

Future studies should utilize emergence sampling to reduce uncertainty in forest pest monitoring. This approach will eliminate the potential for cross-contamination (insect immigration) between samples and will ensure the independence of observations. Particularly, insect identification would be more possible and informative than the process attempted in this study. Ideally, this study would have included an emergence study in the late spring as outlined by Jacobi et al. (2021). Emergence studies often involve secluding firewood samples in containers or nets throughout the spring and identifying the insects that emerge. This method is more reliable than attempting to identify the insects based on the galleries left behind or identifying insects based on larvae due to the similar morphology between many species (Pournou 2020).

4.3 Management Implications

Urban forests are a critical and threatened part of Colorado's front range cities. Although trees have not historically populated Colorado's Front Range (beside riparian corridors), 150 years of silviculture and stewardship have created urban forests that provide ecosystem services, economic wealth, and public health to communities in this corridor (Alexander et. al 2019). Ash trees alone provide 33% of Fort Collin's canopy cover and provide 26% of the urban forest's carbon sequestration (Alexander et. al 2019; City of Fort Collins 2020). If outbreaks were to continue unregulated, particularly EAB outbreaks, a reduction of approximately 25% of the city's canopy cover can result in significant reductions of ecosystem services and can cost local governments hundreds of thousands in remediation, removal, and replanting costs (City of Fort Collins 2020; Koch et al. 2012; Solano et al. 2020). Due to the proximity to native forests, spillover outbreaks of various native Ips beetles, mountain pine beetles, borers such as *A. quercicola* (gamble oak borer), and tree diseases are common (Alecander et. al 2019; Negron & Cain 2019).

Resilient forest planning will be necessary to overcome additive mortality from forest pest outbreaks. Colorado's Front Range Forests already face drought, late season frosts, and elevated temperature fluctuations (Alexander et al. 2019). These climatic factors are expected to become more extreme in the near future as climate change continues to reshape weather patterns, hydrology cycles, fire regimes, and other processes that forests rely on for functional ecosystem health (Esperon-Rodriguez et. al. 2022). Additionally, little is understood regarding insect and pathogen diversity creating the need to build forest systems that can withstand both novel infections and increased prevalence of existing pathogens (Rabiey et. al 2022). Resilience to pest outbreaks can be built through proper forest inventorying, monitoring, diverse canopy planning, planting ahead of losses, enforcement of current laws and quarantines, training foresters in detection methods, and persistent public education (Alexander et al. 2019; Diss-Torrance et al. 2018; Jactel et al. 2017; Lantshener 2023; Solano et al. 2020).

Information from this survey can be used to provide baseline data to urban and rural forestry managers to map the progression of forest pest outbreaks and establish areas of high risk, particularly along the Front Range of Colorado. Current models exist to map the spread of invasive insects such as those developed by Koch et al. and Bendor et al. (2012 and 2006). Canopy databases such as the *Colorado TreeView* can be used to establish possible outbreak routes and determine areas that may be at high risk or in need of quarantine (Alexander et. al 2019). Previous models assume that incidence is low within local firewood. However, this study suggests that local firewood is the product of additive spillover events from other sources that ultimately have a high probability of spreading forests pests. Most firewood is transported less than 100km from its origin, but dispersal events have reached as far as 5,500km (Koch et al. 2012). Previous models also rely on relatively few firewood-specific studies that are now decades old. This study provides current data and expanding insight into forest pest dispersal via firewood.

Monitoring and public outreach will have limited success without an improved regulatory framework to limit the spread of invasive forest pests. Models such as those developed by Tobin et al. and Koch et al. illustrate that strict quarantines in infested regions, firewood treatment, and regulations against imported firewood could significantly slow the spread of species such as EAB and the Asian longhorned beetle (2010; 2012). Although the city of Boulder initiated a quarantine after the initial discovery of EAB, the program was short-lived due to lack of funding and enforcement infrastructure (City of Fort Collins 2020). This may have led to new satellite infestations in Fort Collins and Aurora. Prior to the quarantine's dissolution, inter-agency cooperation and enforcement successfully slowed the spread and prevented massive canopy loss (Alexander et al. 2019). Additionally, the success of firewood treatments such as kiln drying, steam treatments, and others are both limited and difficult to implement on a large scale without massive vendor costs (Chen et al. 2017; MacQuarrie et al. 2020; Tobin et al. 2010). As such, strict regulations and enforcement in areas of high incidence will have the greatest impact on forest pest dispersal (Tobin et al. 2010). Currently, the Animal and Plant Health Inspection Service (APHIS) oversees federal quarantines in major outbreak regions. Many eastern states such as Massachusetts, New York, South Carolina, North Carolina, Maryland, and Virginia have different levels of quarantine that range from a hold on wood product exports to mandatory treatments. However, the results from this study and similar illustrate that firewood exports are largely unmonitored and unregulated (Haack et al. 2010). This survey should serve as a call for action for better regulatory guidelines and enforcement infrastructure.

5. Conclusion

We attempted to quantify and sample forest pests within a firewood processing facility. We predicted that imported firewood would contain higher indices of forest pests. We sampled different types of firewood (split pieces and logs) and explored the variation in indice proportions based on origin, tree species, and vendor. We found each of these factors to be significant, but suspect that tree species is the most important covariate based on our data. There is evidence that local firewood is more or equally likely to transport forest pests even if locally burned. Although this sample suggests that local firewood is just as likely to transport forest pest species as imported firewood, our study is ultimately a single screenshot in time. Our data could change year to year based on new infestations, new firewood sources (i.e. vendors or infested forest patches), climate, and quarantines. Ultimately, continuous monitoring will be essential to establish the information needed to predict the transmission potential of firewood based on species, origin, treatment, and moisture content. Future studies should utilize emergence study designs to better analyze incidence and inform dispersal models.

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