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Phenology of the Invasive Balsam Woolly Adelgid, *Adelges piceae* (Ratz.) (Hemiptera: Adelgidae), on Subalpine Fir in Northern Utah

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PHENOLOGY OF THE INVASIVE BALSAM WOOLLY ADELGID, *Adelges piceae* (Ratz.) (HEMIPTERA: ADELGIDAE), ON SUBALPINE FIR IN NORTHERN UTAH

by

Elizabeth L. Rideout

A thesis submitted in partial fulfillment

of the requirements for the degree

of

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in

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ABSTRACT

Phenology of the Invasive Balsam Woolly Adelgid, *Adelges piceae* (Ratz.) (Hemiptera: Adelgidae), on Subalpine Fir in Northern Utah

by

Elizabeth L. Rideout, Master of Science

Utah State University, 2023

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Balsam woolly adelgid, *Adelges piceae* (Ratzeburg) (Hemiptera: Adelgidae) (BWA), is an invasive true fir pest in North America. Native to Europe, BWA was first discovered in Utah attacking subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) in 2017. Recent BWA-driven subalpine fir mortality in northern Utah has prompted the need for baseline biological research to support pest management. Small-bodied and cryptic, BWA is a challenging pest to detect and study, and its voltinism in North America can range from one to four annual generations depending on elevation and climate. This research focuses on describing BWA's phenology with a degree day model and exploring an effective detection method to support management.

Bark sampling was conducted at five northern Utah study sites from August 2020 through fall 2022 to characterize BWA's seasonality on subalpine fir. A bivoltine life cycle was observed each year with adult density peaks occurring in early summer and early fall, respectively. Using these data and hourly air temperatures recorded at each site, a degree day model was developed to predict progression of adult population proportional completion for each generation. The model was used to predict historical and future voltinism for the study sites using BioSIM-estimated and MACA-forecasted climate data, respectively. For most years since 1980, temperatures supported one complete generation at all sites, >50% completion of a second generation at three sites, and a complete second generation at the remaining two sites. Within the next several decades, projections indicated that the three cooler sites will increase in suitability for more than two complete generations. Predictions for the warmest site indicate thermal suitability for three complete generations by ~2080.

Placement of sticky cards near infested tree boles was then assessed for monitoring wind-dispersing BWA crawlers, the first nymphal instar. Mesh-covered, horizontally-positioned cards resulted in consistent crawler captures and reduced bycatch compared with exposed cards in both positions. Timing of crawler abundance peaks aligned with those of bark samples, indicating potential for use of sticky cards in phenological monitoring. The research findings presented herein will support the development of accurate and timely IPM tools for use by forest managers in northern Utah.

(111 pages)

PUBLIC ABSTRACT

Phenology of the Invasive Balsam Woolly Adelgid, *Adelges piceae* (Ratz.) (Hemiptera: Adelgidae), on Subalpine Fir in Northern Utah

Elizabeth L. Rideout

Balsam woolly adelgid (BWA) is an invasive true fir pest in North America. Native to Europe, BWA was first discovered in Utah attacking subalpine fir in 2017. Recent BWA-caused subalpine fir mortality in northern Utah has prompted the need for baseline biological research to support pest management. Small-bodied and blending easily with its environment, BWA is a challenging pest to detect and study. Phenology, or the timing and characteristics of life stages through the year, of BWA varies depending on elevation and climate and is unstudied in Utah. This research focuses on defining aspects of BWA's phenology, including the number of annual generations, and exploring an effective detection method to support sustainable management practices.

Bark sampling of infested subalpine fir at five northern Utah study sites was conducted to determine the number of annual generations exhibited by BWA. One full generation and >50% of a second generation were observed each year with adults in highest abundance in early summer and early fall. Because insect development is dependent on temperature, these data were used in combination with air temperatures recorded at each site to predict the number of annual BWA generations. Using estimated historical and future climate data, the model was used to predict past and future number of generations for northern Utah. Predictions indicated that since 1980, temperatures were suitable for one complete but fewer than two generations at three of the five sites. Within the next several decades, all sites but the warmest are predicted to increase from slightly less than to slightly more than two complete generations. Climate predictions for the warmest site indicate that three complete generations may occur by ~2080.

The use of sticky cards for monitoring immature wind-dispersing BWA was also assessed. Using mesh-covered cards attached horizontally to stakes, crawler captures were high, and bycatch of non-target organisms was low. Timing of crawler abundance peaks aligned with those of bark samples, indicating potential for use in phenological monitoring. These findings will support development of accurate and timely IPM-decision making tools for use by forest managers in the current and future climate of northern Utah.

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CHAPTER I

INTRODUCTION: PHENOLOGY OF THE INVASIVE BALSAM WOOLLY ADELGID, *Adelges piceae* (Ratz.) (HEMIPTERA: ADELGIDAE), ON SUBALPINE FIR IN NORTHERN UTAH

Invasion of the Balsam Woolly Adelgid in the United States

The balsam woolly adelgid (BWA), *Adelges piceae* (Ratzeburg) (Hemiptera: Adelgidae), is an invasive forest insect in the United States (U.S.) native to south-central Europe (Balch 1952, Havill et al. 2020). This species utilizes true fir species (genus: *Abies*) as hosts in the U.S. Likely arriving via imported nursery stock, the U.S. population of BWA was first detected in Brunswick, Maine in 1908 (Balch 1952). Twenty years later, BWA was discovered in the state of California (Annand 1928) and within decades had established populations in several states on both U.S. coasts.

Discovery of BWA in Coeur d'Alene, Idaho in 1983 confirmed the species' range expansion into the Intermountain Region, though noted damage intensity suggested the species may have been present for at least 5 years before detection (Livingston et al. 2000). Because BWA adults are only 1 mm in length, early detection is often limited to the visibility of woolly flocculence produced by the insect that accumulates on tree bark in dense populations. The seemingly slow or delayed invasion into the Intermountain Region – which includes Utah, Nevada, western Wyoming, and southern Idaho (USDA Forest Service n.d.) – may be attributed to detection limitations or the Columbia Basin serving as a geographic barrier within the area’s true fir range (Davis et al. 2020). However, forest landscapes east of this basin contain substantial populations of true fir and therefore host trees for BWA.

Aerial and ground detection surveys conducted in the region between 2006 and 2019 confirmed the presence of BWA in most Idaho counties (Davis et al. 2020) and in Utah in 2017 near Farmington Canyon and Powder Mountain Ski Resort (Rideout et al. 2023). Similar to initial detection in Idaho, extent of damage in Utah indicated that populations may had been established for up to a decade before detection (Davis et al. 2020). These surveys additionally confirmed the presence of BWA in nine Montana counties and seven Utah counties with the easternmost detection in Gallatin County, Montana (2011) and the southernmost in Utah County, Utah (2018) (Davis et al. 2020). As of spring 2023, ten Utah counties have confirmed detections of BWA (Fig. I-1). The species has now been established or detected in at least six eastern states, three northwestern states, one northcentral state, three interior west states, and the state of Alaska (CABI 2020) (Fig. I-2).

Host Susceptibility

Balsam woolly adelgid attacks all species of true firs in the U.S. with varying degrees of associated host mortality likely due to differences in susceptibility linked with genetic variation within and among hosts (Hain 1988). Due to this host specialization, BWA’s potential non-native range is inherently dependent on the range of true firs. Damage severity and mortality patterns vary geographically and have been linked to host species and stand characteristics such as elevation, moisture, and species composition (Johnson et al. 1963, Davis et al. 2022). Tree injury and mortality caused by BWA has occurred on firs of all size classes and diameters (Davis et al. 2022).

Populations of host species on the eastern U.S. coast such as the southern Appalachia-endemic Fraser fir [*A. fraseri* (Pursh) Poir.] have been severely impacted by infestations of BWA, leaving enduring concerns about the conservation of the species and its role in the U.S. Christmas tree industry (USDA Forest Service 1989). In the coastal western U.S., the more susceptible stands are dominated by Pacific silver fir [*A. amabilis* (Douglas ex Loudon) Douglas ex Forbes] with reports of individual tree mortality following attack in as few as three years (Mitchell 1966). These stands have typically occurred on stream bottoms, benches, and near meadows at moderate elevations (900-1,600 m) (Gast et al. 1990).

There are two host species of conservation concern in the Intermountain Region: subalpine fir [*A. lasiocarpa* (Hook.) Nutt.] (Pinales: Pinaceae) and white fir [*A. concolor* (Gord. & Glend.) Lindl. Ex Hildebr.]. Subalpine fir is native to and found in the western U.S. states of Washington, Oregon, Idaho, Montana, Wyoming, Utah, and Colorado (Fig. I-3). White fir can be found in California, Oregon, Utah, Colorado, Arizona, and New Mexico (Fig. I-4). Subalpine fir in Utah is typically found at elevations of 2,400-3,300 m (Alexander et al. 1990) but can be found at elevations as low as 1,800 m and as high as 3,500 m. White fir is most frequently found at elevations between 2,100 m and 2,700 m (Laacke 1990). Fir stands in northern Utah are primarily subalpine fir-dominant but interspersed with and eventually dominated by white fir in the middle to lower latitudes of Utah. Subalpine fir is highly susceptible to mortality by BWA infestation, having exhibited mortality within 3-5 years by stem infestations (Gast et al. 1990). Although BWA is found on white fir, this host has exhibited low rates of mortality (Mitchell 1966). Given the high susceptibility of subalpine fir, it is the focal host species for these studies.

Geographic patterns of infestation have varied across subalpine fir stands in Idaho and Utah. Infestations of BWA in Idaho were first found on subalpine fir growing in frost pockets at low elevations (900 m) (Gast et al. 1990), and one study conducted in the region between 2008 and 2013 determined that a greater number of subalpine fir were infested and dying below than above 1,800 m (Lowrey and Davis 2018). However, many populations have since been discovered in high elevation stands, with the first discovery of BWA in Utah at an elevation around 2,300 m. Populations in Utah have since been found at the lower elevation range of subalpine fir and as high as 3,000 m (Davis et al. 2020) but are most commonly found between 2,000 and 2,800 m elevation.

Life History of the Balsam Woolly Adelgid

There are two known subspecies of BWA in the U.S.: *Adelges piceae canadensis* is generally found in the northeastern states, and *Adelges piceae piceae* is typically found in the western and southeastern states (Foottit and Mackauer 1980, Hain 1988). In its native European range, BWA requires both fir and spruce (genus: *Picea*) hosts to complete its entire holocyclic (sexual) life cycle (Havill and Foottit 2007). However, likely due to the absence of suitable spruce hosts in its introduced range, North American populations of BWA are anholocyclic and reproduce parthenogenically (asexually), producing populations consisting entirely of females (Balch 1952). Parthenogenic reproduction is thought to be a significant contributing factor to the species' invasion success.

A single anholocyclic life cycle of BWA consists of the egg, three instars, and the adult (Fig. I-5). The first instar, termed the crawler, is roughly 0.4 mm in length and the only stage capable of motility. Dispersal among trees and forested landscapes is therefore dependent primarily on crawlers being carried by wind or animals (Balch 1952, Woods and Atkins 1967). Additionally, dispersal can be facilitated by human movement through the transportation of infested nursery stock and firewood, as well as by birds and small mammals (Woods and Atkins 1967, Atkins and Woods 1968). Dispersal on and among trees occurs during the crawler's unsettled phase, a stage in which the crawler moves around the bark in search of a suitable feeding site. Once a feeding site is chosen, the crawler settles by inserting its piercing-sucking mouthparts (stylets) into the tree bark and beginning to feed on the tree's nutritious parenchyma cells (Hain 1988). This may occur in as little as two to three hours from hatching (Balch 1952). It is in this life stage that most overwintering is hypothesized to occur in a dormant or diapause state (Balch 1952, Amman 1962), though no empirical studies have addressed diapause induction or maintenance. A summer pause in development, or aestivation, in the crawler life stage has also been hypothesized (Amman 1969). Once settled, the crawler will begin exuding woolly threads for protection and bark adherence and darkening in body color, resembling the second instar nymph, before molting. In dense populations, these woolly masses, referred to as “woollies”, are critical for visual detection of infestation (Fig. I-6).

The second instar is defined by a slight increase in body length, relative to the crawler, to roughly 0.5 mm, a broader and more dorsally convex body shape, and purplish-black coloration. This nymphal stage becomes gradually covered in long wax threads and eventually molts to the third instar, defined by an increase in body length to roughly 0.6 mm and a more rounded body shape (Balch 1952). The third instar then molts to the final stage, the adult, which is defined by a body length of 0.7 to 1 mm, a hemispherical body shape, and a posterior end slightly more pointed where the ovipositor is located. The adult will begin oviposition two to three days after molting and may continue to do so for five or more weeks, laying up to ten eggs per day in some regions. The egg incubation period lasts for nearly two weeks (Balch 1952).

BWA has demonstrated variable life history traits including seasonality, voltinism (number of annual generations), and periods of dormancy among its introduced regions of the U.S. In warmer and lower-elevation climates such as those of the East Coast and Pacific Northwest, BWA has demonstrated up to four generations per year in the lowland areas, three in the intermediate elevations, and two in the higher elevations, with an additional partial generation arising in warmer years (Mitchell et al. 1961). In the provinces of Maritime Canada, BWA most often has one or two annual generations (Greenbank 1970). It’s predicted that BWA exhibits at least two full generational cycles in the Intermountain Region given the elevation range of its hosts' habitat. Early research on the U.S. east coast suggests that BWA enters two periods of hibernation as a crawler, namely a diapause in winter and a short period of summer aestivation in the following generation (Amman 1969), though neither behavior has been confirmed in the Intermountain Region. This geographical variability in life history of BWA presents the critical need for further research on its basic biology in the region to conserve host stand integrity and facilitate successful management.

Host Plant-Insect Interactions

All life stages of BWA (excluding the eggs, which are non-feeding) attack the bark of the main stem of the fir host with the infestation eventually spreading to branches and twigs in dense populations. Preference for initial establishment by crawlers has been noted on the tree's base, possibly because snow insulation may enhance overwintering success (Greenbank 1970). The insects may also choose to settle in the crevices of the bark, though there is little consistent evidence that this is a preference.

Feeding commences when the crawler inserts its stylets into the bark, passing through the phellem (outer layer of the bark) and probing to find the tree's nutritious cortical parenchyma cells. The phloem may be penetrated slightly during feeding, though typically only in young shoots (Balch 1952). The adelgid injects salivary toxins when feeding which often leads to the swelling of the tree's branches, called gouting (Fig. I-7) (Balch 1952). Crawlers have demonstrated preference for these swollen limbs, presumably because the parenchyma was stimulated by a previous adelgid's salivary injections (Balch 1952). Feeding continues through each subsequent stage of development with the insect partially removing its stylets from the bark during molts. Where feeding has occurred, tolerant firs may develop a secondary periderm layer over the damaged cambium tissue, preventing subsequent BWA from feeding at that location (Balch 1952). Susceptible firs may incompletely form this secondary layer or not at all (Hain 1988). Cell structure and function may be compromised by extensive BWA feeding (Hain et al. 1991), ultimately leading to restricted water flow and reduced photosynthesis and respiration in the host tree (Mitchell 1967, Puritch 1973).

Symptoms of infestation by BWA within the host tree may be internal or external. Internal symptoms are largely caused by the injection of toxic saliva that alters cambium, xylem, and phloem cells (Johnson 1959, Mitchell 1966). These internal symptoms include an increased number of xylem cells per annual ring, shortened and rounded tracheids, and, in some hosts, an increased number of traumatic resin canals and ray cells (Hain 1988). The latter symptom often appears as thick, darkened reddish rings, also called *rotholz*, though this symptom has not been observed associated with BWA in the Intermountain Region. Increased numbers and size of parenchyma cells in the feeding zone may also occur (Hain 1988). In addition to branch gouting, common external symptoms of BWA feeding include branch flagging, or browning and dying of individual branches throughout the tree crown, and loss of the host tree's apical dominance. In as few as three years after initial infestation, crown dieback and eventual tree mortality can be observed in subalpine fir (Mitchell 1966, Cook et al. 2010).

Relationships between BWA presence and other biotic factors may also accelerate mortality of the host. This may include interactions caused by the presence of other true fir pests such as fir broom rust, mistletoe, wood-boring or defoliating insects, and wood rots. For example, an increase in the presence of *Armillaria* root rot infestations has been correlated with presence of BWA on balsam fir in Newfoundland, Canada (Hudak and Singh 1970). This relationship may also increase the likelihood of true fir mortality from multiple stressors, including BWA and defoliator feeding (Mitchell and Buffam 2001).

Integrated Pest Management of the Balsam Woolly Adelgid

The vast landscapes of suitable true fir habitat in the Intermountain Region will likely support continued range expansion of BWA, suggesting the need for effective pest management techniques. The integrated pest management (IPM) approach engages a suite of strategies aimed at effectively managing pest populations while maintaining environmental integrity of the landscape. This approach generally includes a diverse combination of biological, chemical, and cultural control methods and decision support tools such as biologically-based models. Regardless of the tactic implemented, baseline research on the pest's phenology and effective monitoring techniques are critical for successful insect pest management (Lowrey and Davis 2018).

Pests may be monitored through a variety of tools with traps being one of the most convenient for pest managers. Trap options include those baited with odor or visual attractants or strategically placed for passive encounter by target organisms

(Epsky et al. 2008). Examples of effective traps for insects include pheromone, pitfall, and sticky card traps. Monitoring may be conducted for the purposes of general ecological studies (Bechinski et al. 1990, Broatch et al. 2006), informing timing of pesticide applications (Lewis 1981, Merrill et al. 2010), or determining the starting date for phenology models (Knutson and Muegge 2010, Dupuy et al. 2017). Due to the small body size and cryptic nature of BWA, monitoring is typically reduced to visible detection of tree infestation symptoms such as woollies on the tree bole or branch node swelling (gouting). Detection of BWA life stages or symptoms on host trees is labor- and time-intensive and mainly effective only when population sizes are large. More research on monitoring approaches for BWA is critical to support adoption of IPM practices (Johnson et al. 2005).

Biological control of BWA is challenging because there are no known specialist parasitoids. Introduction of predatory natural enemies of BWA has been attempted several times in North America where BWA is established. A total of 33 predator species were released in various areas from 1933 to 1969 (Montgomery and Havill 2014). Of these, six species successfully established in both the U.S. and Canada: *Aphidecta obliterata* (Linnaeus) and *Scymnus impexus* Mulsant (Coleoptera: Coccinellidae), *Laricobius erichsonii* Rosenhauer (Coleoptera: Derodontidae), *Cremifania nigrocellulata* Czerny and *Neoleucopis obscura* Mills (Diptera: Chamaemyiidae), and *Aphidoletes thompsoni* Möhn (Diptera: Cecidomyiidae) (Clausen 1978, Schooley et al. 1984). Despite establishment and evidence of predation on BWA, there is no evidence that these introductions resulted in significant reductions in pest populations or improved tree survival (Montgomery and Havill 2014).

Chemical control techniques such as aerial insecticide applications for large-scale BWA management are costly and limited in efficacy due to the insect's small body size, protected feeding sites, and waxy body covering, leading to challenges with contact of the insect (Ragenovich and Mitchell 2006). Thorough insecticide applications to individual high-value trees from the ground may provide management of BWA in areas such as ski resorts, campgrounds, and cabin sites (Ragenovich and Mitchell 2006). In some areas of the U.S., chemical management in Christmas tree farms has been successful using a single application of a pyrethroid insecticide – esfenvalerate or permethrin – or insecticidal soap (Hastings et al. 1986). Success in these practices has only been demonstrated in nursery and tree farm settings thus far.

Cultural control methods are likely the most viable management option for BWA in the Intermountain Region (Ragenovich and Mitchell 2006). These tactics include selective removal of heavily infested trees during inactive periods of the dispersing life stage and favored planting of non-host tree species and genetically resistant strains (Ragenovich and Mitchell 2006).

In combination with these management techniques, decision support systems are essential tools for integrating scientific knowledge with end-users making management decisions (Prasad and Prabhakar 2012). Important among these support systems are models that inform appropriate timing of management techniques. Because the BWA life stage responsible for dispersal is the crawler, it is critical that management actions such as insecticide applications or tree felling consider crawler activity levels for maximum efficiency.

Phenology models, such as degree day models, use daily temperature, basal temperature thresholds for insect development, and knowledge of insect phenology to estimate the number of heat units, or degree days, required to accumulate within the year to prompt occurrence of a biological event of interest (Murray 2020). A degree day model that incorporates region-specific phenology and air temperature data for BWA could inform timely monitoring and management decisions in Utah.

Furthermore, degree day models can be expanded to understand historical and future pest phenology for maximum efficiency of management tactics. Phenology forecasting models use knowledge of the pest's phenology alongside forecasted climate data to predict the likelihood of events such as novel pest establishment, the timing of outbreaks, or voltinism (Knight and Cammell 1994, Abolmaaty et al. 2011, Bentz et al. 2019). Climate data may be forecasted for several different representative concentration pathways (RCPs), or sets of trajectories that represent different greenhouse gas concentration scenarios. Commonly used scenarios include RCP 4.5 which describes a future climate scenario based on intermediate climate change mitigation efforts and RCP 8.5 which represents the worst-case climate change scenario with continual, rapid rise of greenhouse gas emissions.

Research Justification

Balsam woolly adelgid has exhibited range expansion and ecological characteristics that suggest a likelihood of continued expansion in Utah and the Intermountain Region. Successful management of an insect pest in an IPM framework includes baseline phenological research and effective monitoring techniques. Lack of phenological understanding of BWA in the region and established, accessible monitoring techniques has made management of BWA challenging. Phenological research and development of effective monitoring and management tools are therefore critical for managing this invasive insect in the Intermountain Region.

The research described in this thesis aims to understand and model fundamental aspects of the phenology of BWA in northern Utah. In Chapter II, regional phenological characteristics of BWA are described via intensive life stage sampling of infested subalpine fir trees at five northern Utah study sites. These data were collected across an elevational gradient and through time to assess key phenological characteristics of BWA in northern Utah such as voltinism and overwintering activity. These data were incorporated with air temperatures recorded at each site to develop a degree day model to estimate the peak timing of BWA life stages and generations in northern Utah. This model was further enhanced to provide insight on historical and forecasted voltinism at the study sites based on a future climate scenario following the current climate trajectory. The intended uses of these models are to 1) inform land managers on appropriate timing of monitoring and management action against BWA in Utah, and 2) support efficient future population management by forecasting BWA voltinism.

In Chapter III, a method using sticky card traps for monitoring dispersing BWA crawlers was explored. This method was compared to bark sampling described in Chapter II for efficacy and accessibility for use by land managers. Overall, this research will define foundational phenological aspects of BWA in the region and facilitate the success of its management in the current and predicted future climates of northern Utah and similar areas in the Intermountain Region.

Objectives

Objective 1 (Chapter II). Develop a degree day model to predict BWA phenology within a seasonal cycle, including peak activity of key life stages, and explore evidence for dormancy events. Additionally, use the model to predict historical, current, and future BWA voltinism at study sites in northern Utah.

Objective 2 (Chapter III). Compare a sticky card approach with the bark sampling method for efficacy and accessibility in monitoring dispersing BWA crawlers.

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Figures

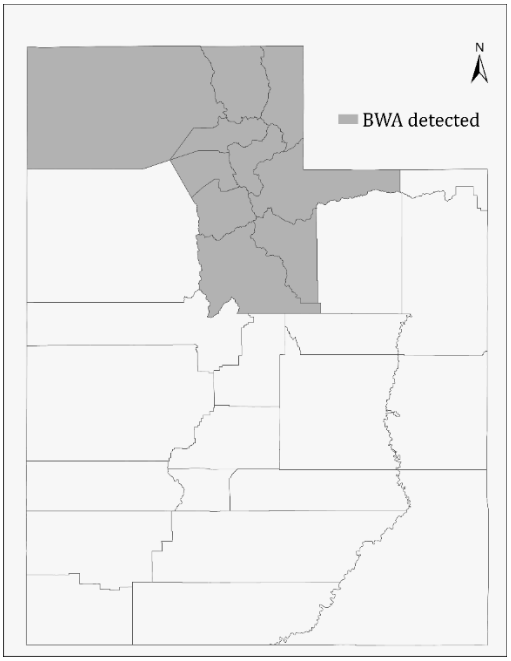

Figure I-1. Map of Utah counties with confirmed detections of balsam woolly adelgid as of Jun 2023.

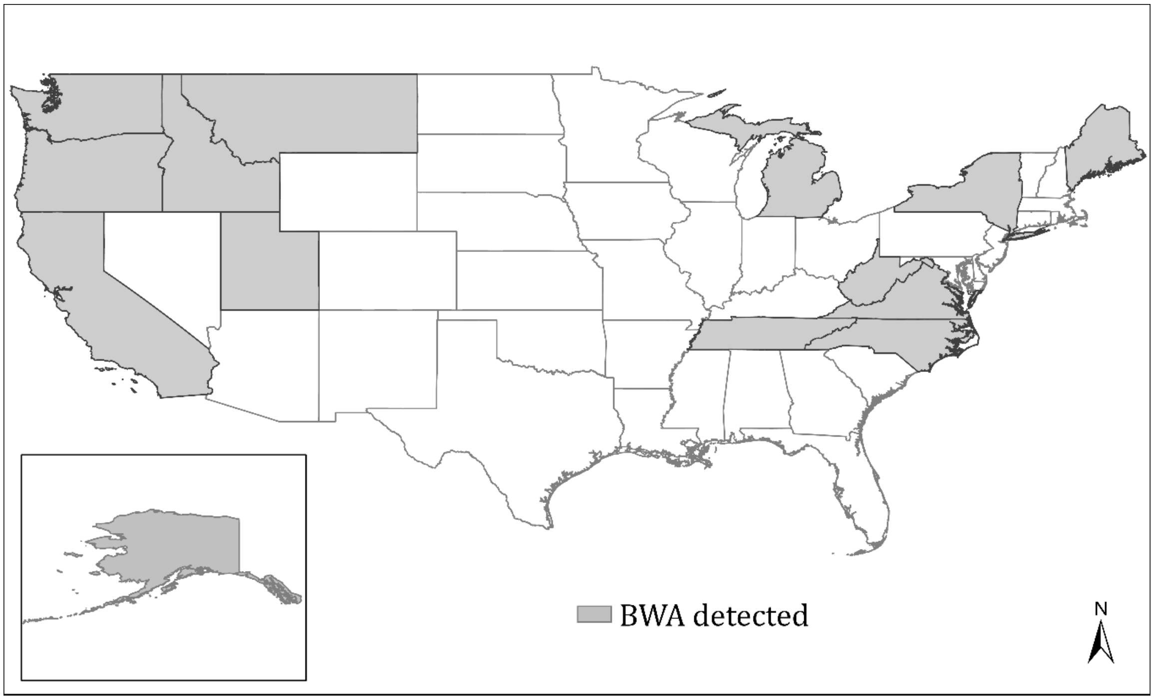

Figure I-2. Map of U.S. with confirmed state detections of balsam woolly adelgid as of Jun 2023.

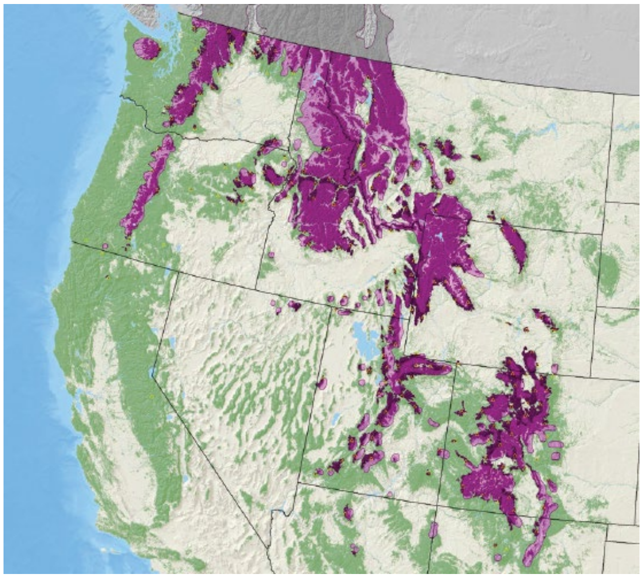

Figure I-3. Range map of subalpine fir (*Abies lasiocarpa*) in the western U.S. (Krist et al. 2015).

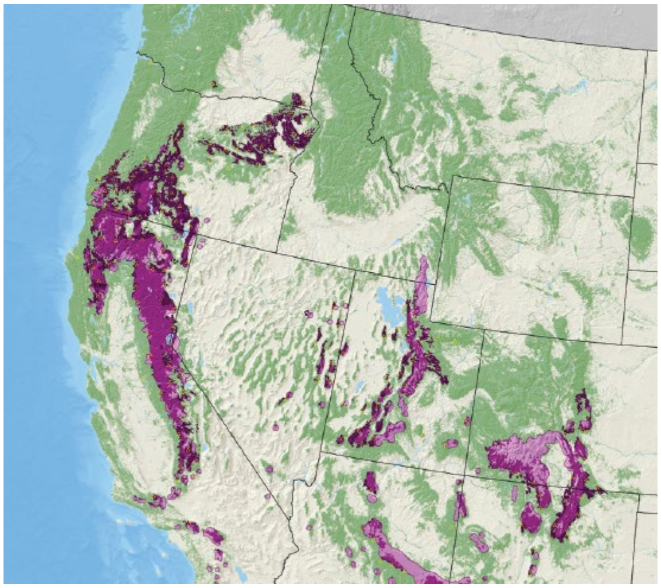

Figure I-4. Range map of white fir (*Abies concolor*) in the western U.S. (Krist et al. 2015).

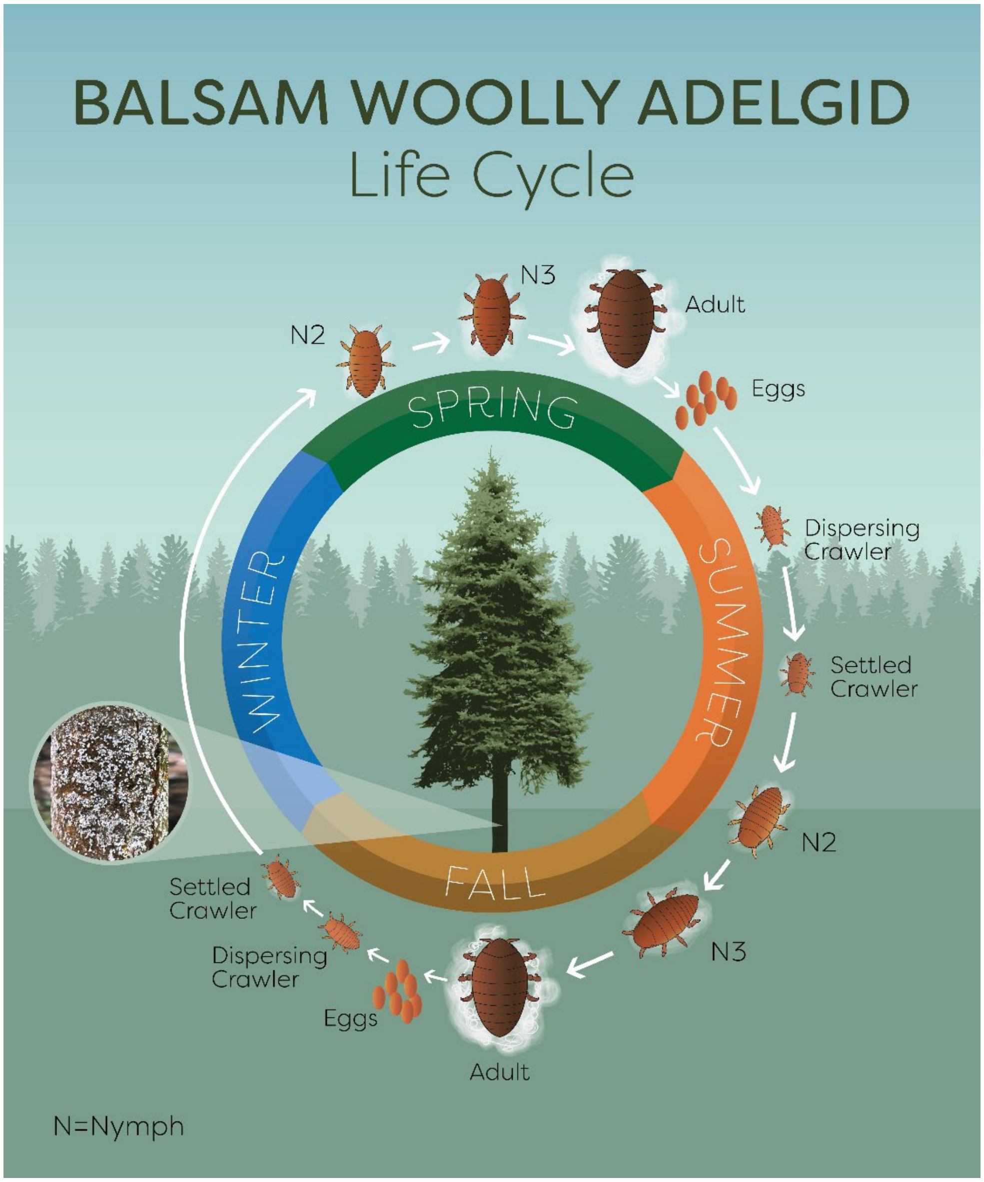

Figure I-5. Bivoltine life cycle illustration of the balsam woolly adelgid in northern Utah (illustration and graphic design by Michael Langenheim, USU Extension).

Figure I-6. A subalpine fir bole heavily infested by balsam woolly adelgid; note the diagnostic white woolly masses produced by the insect.

Figure I-7. Gouting, or the swelling of branch nodes, is a characteristic symptom of feeding by balsam woolly adelgid.

CHAPTER II

A DEGREE DAY MODEL FOR PREDICTING VOLTINISM OF THE BALSAM WOOLLY ADELGID, *Adelges piceae* (HEMIPTERA: ADELGIDAE), IN NORTHERN UTAH[1]

Abstract

Balsam woolly adelgid, *Adelges piceae* (Ratz.) (BWA), was first confirmed attacking subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] in Utah in 2017. Voltinism of BWA varies with elevation and climate; characterization of its life history in the Intermountain Region will support pest management decision-making. Bark samples were collected from infested subalpine fir at five northern Utah sites in summer and fall (weekly) and in winter and spring (biweekly to monthly) from Aug 2020 to Dec 2022. Life stages of BWA were counted and seasonal phenology determined. Degree day (DD) models for each generation were developed by fitting proportional adult counts and hourly air temperatures to a Weibull distribution. Eleven parameter combinations with a 1 Jan biofix and lower developmental thresholds (LDT) from 0 to 10°C were tested for optimal model fit. Model fit was optimized with a 0°C LDT. Two annual generations were exhibited, with 95% completion of the first and second generations requiring 998 DD and an additional 1,685 DD, respectively. Slower development in Jul and Aug during peak temperatures suggest an aestivation period. Predictions of historical (1980-2019) voltinism for the study sites showed a trend towards increased thermal suitability to support two generations. Forecasted temperatures (2020-2099) suggest that in

the next several decades, thermal suitability for more than two generations will remain low, and three generations will not be supported until the end of this century. The DD model will be a useful tool for forest managers to inform timely BWA treatments and forecast voltinism trends in the region.

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[1] Coauthored by Diane G. Alston and Barbara J. Bentz

Introduction

The balsam woolly adelgid, *Adelges piceae* (Ratz.) (Hemiptera: Adelgidae) (BWA), is an invasive pest of true firs (genus: *Abies*) in North America. Native to south-central Europe, BWA was first detected in North America in Brunswick, Maine in 1908 (Kotinsky 1916, Havill et al. 2020) and is now established in the United States (U.S.) on the east coast as far south as North Carolina and in the Pacific Northwest. In Canada, BWA is established in the southernmost coastal provinces. Range expansion into the U.S. Intermountain Region was first confirmed in Coeur d'Alene, Idaho in 1983 (Livingston and Dewey 1983) and later in Farmington Canyon, Utah in 2017 (Rideout et al. 2023). Balsam woolly adelgid has now been documented in many subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.] stands in northern Utah and is considered a significant contributing factor to recent fir mortality (Rideout et al. 2023). Subalpine fir is a critical species for maintaining healthy watersheds, providing wildlife habitat and forage, and sustaining recreational tourism industries in northern Utah.

In North America, BWA is parthenogenic and exhibits an anholocyclic life cycle with three instars. The first nymphal instar, the crawler, is the only motile stage and is responsible for dispersal, usually by wind (Balch 1952). The crawler is also believed to be the overwintering life stage, though other life stages entering winter have been reported (Balch 1952). Winter diapause and summer aestivation in the crawler stage are hypothesized but have not been thoroughly investigated. Once hatched from the egg, the crawler inserts its stylets into the bark and begins feeding on the tree's parenchyma cells and exuding white, waxy threads called ‘wool’. The settled crawler molts through two sessile nymphal stages and upon reaching the adult stage is characterized by a heavy wool covering. Difficult to recognize when populations are low, higher densities of woolly masses contribute to population detection. Feeding by BWA leads to restricted water flow and reduced photosynthesis in the host tree, often presenting as drought-like symptoms (Mitchell 1967, Puritch 1973).

Previous studies have shown that BWA’s seasonality is temperature-dependent and varies with elevation and climate. Three BWA generations were reported in North Carolina (elevation ~1,500 m) (Arthur and Hain, 1984) and between two and four generations in the U.S. Pacific Northwest (elevations 70-1,200 m) (Mitchell et al. 1961). In continental New Brunswick, Canada (elevation ~100 m), between one and three generations of BWA were observed (Greenbank 1970). Northern Utah geography is characterized by high elevations with a climate of warm, arid summers and substantial winter snowfall, a unique combination compared with previously invaded and studied regions.

Given BWA’s recent invasion of northern Utah, knowledge of BWA seasonality and the number of annual generations in the region would inform management strategies that include infested tree removal and single-tree insecticide treatments. Degree day models are a widely used tool in integrated pest management (IPM) for predicting critical life history events such as the timing of insect life stages and voltinism (Murray 2020). Degree day models have been developed for other forest insects such as hemlock woolly adelgid (*Adelges tsugae* (Annand)) (Tobin and Turcotte 2018), velvet longhorned beetle (*Trichoferus* *campestris* (Faldermann)) (Haynes et al. 2022), and spotted lanternfly (*Lycorma deliculata* (White)) (Smyers et al. 2021).

The goals of this field study were to describe BWA phenology in northern Utah and develop a degree day model for estimating life stage timing and voltinism. Balsam woolly adelgid life stages were sampled in multiple years from infested trees in five subalpine fir stands across a range of elevation and latitude. Using air temperatures measured within each stand, a degree day model for BWA adults was developed and used to predict the number of annual generations expected in historical, current, and future climate scenarios at each location.

Materials & Methods

Phenology Sampling

This study was conducted at five BWA-infested subalpine fir stands located within the Uinta-Wasatch-Cache National Forest (Table II-1). Sampling began in Aug 2020 at Rock Canyon, Laketown, and Green Canyon and in Jun 2021 at Big Mountain Pass and Farmington Canyon. All sites except Farmington Canyon were sampled through Dec 2022. Due to limited sampling ability caused by low BWA populations, Farmington Canyon was discontinued in Jun 2022. Winter and spring access to sites was restricted due to snow; therefore, regular weekly samples were collected from all sites from 1 Jun through 30 Nov. In 2021 and 2022, winter and early spring samples were also collected biweekly to monthly at Green Canyon, the one site accessible by the use of skis or snowshoes.

At each site and sampling interval, 6.45 cm^2 (2.54 cm × 2.54 cm) bark samples were removed from four to eight BWA-infested subalpine fir trees using a 2.54 cm (1 in) width wood chisel (DeWalt Industrial Tool Company, Towson, MD, USA). Samples were placed in individual 50 mL centrifuge vials (VWR International, Radnor, PA, USA) and returned to the USDA Forest Service Rocky Mountain Research Station in Logan, Utah. Bark samples were initially collected from three bole heights in 2020 (the tree base, 1 m above the base, and 2 m above the base) from five trees at Green Canyon and four trees each at Rock Canyon and Laketown. Using the 'glmmTMB' and 'Anova' functions from the 'glmmTMB' and 'car' packages, respectively (R Core Team 2022), a binomial linear mixed effects model based on data from Aug to Nov 2020 indicated no differences in proportional adult counts over time between bole heights ($\chi^2 = 1.71$, df = 2, p = 0.425). In 2021 and 2022, the 2 m height was removed from the protocol to reduce sampling and processing time. Ongoing samples were collected from two heights and two aspects (north and south) on individual trees such that samples from every aspect/height combination were obtained in each sampling interval. At the start of each sampling season (i.e., ~1 Jun), new study trees were selected to reduce potential negative impact of bark removal on BWA populations. Regular sampling subsequently occurred on 27 trees at five study sites in 2021 and 16 trees at four study sites in 2022.

On each bark sample, adelgid life stages (egg, instars 1-3, adult) were counted with the aid of a stereoscope (magnification 25×). Life stage was determined by size and shape (Balch 1952). Settled crawlers often appear dark and similar to second instar nymphs; therefore, all crawlers (unsettled and settled) and second instars were grouped as "early instars." To include adelgids that dislodged from bark samples, collection tubes were rinsed with distilled water, the rinsate poured into a petri dish, and adelgids counted and added to the bark sample total counts.

Small adjustments in protocols for processing bark samples and designation of living adelgids led to methodology improvements during the study period. In 2020 and 2021, samples were stored in 95% ethanol, and live insects were distinguished from dead individuals beginning only in 2021. In 2022, bark samples were processed immediately after collection or stored at 5°C for no more than three days before processing. Live and dead status of individuals in 2022 samples was determined following Mech et al. (2018) for hemlock woolly adelgid. Briefly, individual adelgids were removed from the bark and observed for stylets or body movement; if neither was observed, the adelgid was pierced and exuding hemolymph was observed for appropriate viscosity and color. If the adelgid exhibited stylets or body movement or the hemolymph was fluid and deep red-purplish, the adelgid was considered alive. If no movement was observed and the hemolymph was dry, the adelgid was determined to be dead. Living eggs were defined by reddish-brown coloration and intact oval shape; dead eggs were determined by a lack of color and a shriveled appearance. Living status of adelgids in ethanol-stored samples (2021) was examined only by piercing and hemolymph observation. The bodies of adelgids found in the rinse solution from collection tubes were pierced to observe exuding hemolymph for viscosity and color, and living status was assigned as for bark samples.

To plot adelgid seasonality, weekly sample data for each life stage were z-score standardized by tree across the sampling range for the tree. Z-scores among trees were then averaged for a given sample date at each site and a local regression (LOESS method) was fit to the standardized values.

A minimum of 15 adults from each field site were identified to species level using PCR and confirmed with DNA barcoding and morphology of slide-mounted specimens using methods described in Havill et al. (2021).

Degree Day Model

A Campbell Scientific CR1000 datalogger with air temperature probe 107 (Campbell Scientific, Inc., Logan, UT) was installed at each site to record hourly air temperatures. Temperature data for 2020 prior to installation of dataloggers were extrapolated from two or three weather stations in close proximity and of similar elevation to each site (https://download.synopticdata.com/). Linear regressions were performed using the associated weather station and site-observed maximum and minimum temperature data ('lm' function, R Core Team 2022). The linear model was then run in Microsoft Excel (Microsoft Corporation 2018) using the regression parameter values to output daily maximum and minimum temperatures. Daily hourly temperatures were estimated using a sinewave function (MATLAB R2022b, Math Works 2022).

Degree days (DD) were calculated from daily hourly data for each year and site using trapezoid integration ('trapz' function, MATLAB R2022b) with an upper and lower threshold. Accumulations were calculated using a 1 Jan biofix (DD_0), a common threshold used in insect phenology models that indicates when heat accumulation calculations begin. Because no developmental thresholds have been determined for BWA, eleven lower developmental thresholds (T_0) (0°C-10°C) were tested. The upper developmental threshold temperature (T_1) was kept constant at 30°C because degree day calculations indicated that the DD for BWA were relatively insensitive to variations in T_1 over a range of 20-30°C, and temperatures at each study site rarely exceeded 30°C. Support exists for using these methods of testing when an empirical biofix or laboratory-tested developmental thresholds have not been established for a species (Akotsen-Mensah et al. 2011, Dupuy et al. 2017, Mo and Stevens 2021).

All life stages were evaluated for use in a degree day model; however, the adult stage was chosen for the final model due to its reliability for accurate identification and prevalence in bark samples. Generation start and end dates for each site-year were chosen by visually estimating trends in z-score standardized weekly adult count values as calculated previously. Cumulative adult proportions were then calculated as the count per date divided by the total count for an individual tree across the date range for each generation. Due to limited site accessibility in the spring, cumulative adult proportions for the first summer generation were not calculated by tree, but were summed across sample dates.

Adult proportions within a generation were predicted for each parameter combination by 1) matching the observed proportions to the specified T_0 and DD_0 combination values by sampling date, resulting in 11 unique datasets, and 2) fitting the cumulative proportions (P) and DD of each dataset to the cumulative Weibull distribution function (Weibull 1961):

$$\text{PDD} = 1 - \exp(-(\frac{DD}{\lambda})^{k}) \tag{1}$$

where λ and k are parameters to be estimated ('minpack.lm' package, 'nlsLM' function). A linear regression ('lm' function) was fitted to the Weibull output and optimal model parameter values determined by selecting the T_0/DD_0 combination with the highest coefficient of determination (R^2) between observed adult proportions and those predicted by the model across all sites (Smith and Rose 1995). A coefficient of determination close to one indicates a strong relationship between the observed and predicted adult proportion values. The optimal parameter values were used for development of each generation degree day model.

The degree days at which a given proportion of adults may be present was estimated by the inverse of the cumulative Weibull distribution function [Equation (1)]:

$$\text{DDP} = \lambda * (-\log(1 - P))^{1/k} \tag{2}$$

Models were developed for each generation observed at the study sites. Due to limited winter and early spring site accessibility, the first generation was modeled using only data from the winter-accessible Green Canyon site and the spring-accessible Big Mountain Pass site. Data from all sites were used to estimate parameters for the second generation. Life stage count data from 2021 and 2022 had living status determination and were assumed to be most accurate; these data were therefore used for model development, and 2020 site-years were used for model evaluation. Due to limited first-generation data, these models were not evaluated against independent datasets. Each model was also evaluated using the datasets used for associated model development.

Predicting Voltinism

Historical daily maximum and minimum temperatures for each study site were generated using BioSIM 11 (Régnière et al. 2017) for the years 1980-2019. BioSIM generates site-level daily maximum and minimum temperatures based on nearby weather stations, adjusting for latitude, elevation, and topography. Hourly temperatures were estimated from daily maximum and minimum temperatures based on a sinewave function, and degree days were estimated based on numerical trapezoidal integration as previously described. To project future temperatures (2020-2099) for each study site, data from ten Global Climate Models (GCMs) parameterized under the most aggressive scenario in assumed fossil fuel use, Representative Concentration Pathway (RCP) 8.5, from the Multivariate Adapted Constructed Analogs (MACAv2) downscaled climate model dataset (Abatzoglou and Brown 2012) were used. Mean daily maximum and minimum temperatures were calculated across GCMs, then total annual DD were calculated using the resulting temperature datasets with the method previously described.

Historical and future trends in voltinism were predicted using the DD model developed for two generations. Because the model provides output that is continuous, annual predictions of one plus a partial second generation or two complete generations were estimated. Because there are no observations of temperatures that support more than two generations in our field data, for years with DD greater than the requirement for 99% completion of a second generation, the proportion completed of an additional generation was estimated by calculating 1) an "upper" estimate, where the assumption is that additional generations require DDs similar to that required for completion (99%) of the first generation observed in this study, and 2) a "lower" estimate, where the assumption is that additional generations require DDs estimated for completion (99%) of the second generation. While these additional generations were not observed in this study, these assumptions are meant to encapsulate the upper and lower ends of feasibility in the cases of additional generations.

Results

BWA Phenology

Among the sample counts for which living status was assigned (2021 and 2022), live individuals of each life stage or group (i.e., early instars) were present on the majority of sampling dates (Fig. II-1A-E) including in late fall, winter, and the first spring sampling dates at Green Canyon, the only winter-accessible study site (Fig. II-1A). The proportional abundance of early instars, however, was considerably higher than other life stages in winter and spring. Despite finding live individuals of all life stages throughout the year, two peak periods of adults, which varied among site-years, were observed in standardized counts. These results suggest two BWA generations in a single year at the study sites. The first adult peak, F1 generation, occurred in early summer and the second peak, F2 generation, in late summer and fall (Fig. II-1A-E). Restricted access due to snow limited spring sampling; therefore, the F1 generation adult peaks were best observed at Green Canyon (Fig. II-1A), although the F2 generation adult peaks were observed at all sites. A period of low counts in all life stages was observed at some sites in Jul and early Aug following the first adult peak.

Degree Day Model

Lower threshold values (T_0) between 0 and 10°C were tested to determine the best fit between observed and predicted adult proportions. When using DD_0 = 1 Jan, T_0 = 0°C explained the most variability ($R^2 = 0.75$) (Table II-2) and was used to estimate parameters for both the F1 and F2 generation models (Fig. II-2). Each model was based on cumulative DD > 0°C beginning 1 Jan and ending 31 Dec of the same year.

Model predictions estimated 998 DD > 0°C were required for 95% completion of the F1 generation in early summer and 2,683 DD > 0°C for the F1 and F2 generations combined (Table II-3), suggesting that completion of the F2 generation requires more DD > 0°C than the F1 generation. Due to limited ability to conduct spring sampling, the F1 model was not evaluated with an independent dataset, though it showed high predictive accuracy against the datasets used in model development ($R^2 > 0.97$) (Table II-4). Greater than 92% and 78% of the variation was explained in predicting the F2 generation respective to independent (2020 data) and dependent (data used in model development) evaluation datasets (Table II-4). Using the F2 generation model and observed temperature data, between 1.5 and 2.0 generations annually were estimated for each site and year (Table II-5).

Predicting Voltinism

Results from the F2 generation model using historical temperatures for the five study sites indicate generally increasing temperature suitability for two BWA generations since 1980 (Fig. II-3). Thermal suitability for two generations occurred most frequently during this time period at Green Canyon and Big Mountain Pass, the two lowest elevation sites. Two generations were predicted for Farmington Canyon in only two years (2007 and 2012), and temperatures at Laketown and Rock Canyon were not sufficient for two complete generations in any year between 1980 and 2019 (1.7 ± 0.02 and 1.63 ± 0.02, respectively).

Forecasted future temperatures from 2020 to 2099 suggest that suitability for more than two BWA generations at the five study sites increases slightly but remains below 2.5 generations for at least the next four decades at all sites. Thermal suitability for three generations is not predicted until the end of this century (Fig. II-4A-E). Under the "upper" assumption (additional generations require DDs estimated for completion of the F1 generation), Big Mountain Pass is predicted to have thermal suitability for three complete generations in 2067, whereas thermal suitability for three generations was not predicted at the highest elevation site (Rock Canyon) until 2098.

Discussion

BWA Phenology & Degree Day Model

Individuals of all BWA life stages were found on bark samples from most sample dates, indicating the presence of overlapping cohorts. In most cases, one or two life stages dominated at a single sample time. Although overlapping cohorts can create challenges in estimating the number and timing of generations, two distinct adult peaks were evident annually at all sites, suggesting two BWA generations and lending support to the use of adult phenology for the degree day model. The regional model developed herein predicts that the F1 generation requires ~1,000 DDs > 0°C from 1 Jan, and an additional ~1,700 DDs for 95% completion of the F2 generation, suggesting that the F2 generation requires more DD for completion than F1.

In comparison, Greenbank (1970) found that univoltine and bivoltine populations on balsam fir in New Brunswick required 650 and 2,200 DD, respectively, using $T_0 = 5°C$, which equates to 710 and 1,915 DD, respectively, using $T_0 = 0°C$. Differences in DD requirements between New Brunswick and northern Utah may be due to host tree species, the adelgid subspecies (*A. piceae canadensis* in New Brunswick versus the likely *A. piceae piceae* in Utah) (Foottit and Mackauer 1980), or potential adaptations in BWA populations in the western U.S. Additionally, degree day accumulations at the sites highlight that more factors than just elevation influence thermal conditions important for BWA. Farmington Canyon, one of the highest elevation sites, had the greatest DD accumulations and Green Canyon, one of the lowest elevation sites, had the lowest DD accumulations (Table II-5). Factors including aspect, slope, shading, and stand density are likely involved in the accumulation of heat within forest stands.

Balsam woolly adelgid crawlers are hypothesized to experience two periods of dormancy: a winter diapause and a summer aestivation (Balch 1952), both defined by arrested development, suppressed metabolism, and increased stress resistance (Gill et al. 2017). These dormancies, often utilized to help the insect withstand adverse weather conditions, may be obligatory or facultative. An obligatory aestivation has been observed in regions where only one generation is completed, though the requirement of this dormancy is less clear when more than one generation occurs (Greenbank 1970). While these processes have not been thoroughly investigated in northern Utah BWA populations, induction of crawler aestivation following the end of the F1 generation in early summer may provide explanation for the low number of individuals observed during peak summer temperatures in Jul and Aug as well as the higher DD requirement of the F2 generation. This apparent slow-down in developmental progression was not consistent across sites or years, indicating that variation in geographic factors related to diapause such as microclimate or population genetics may play a significant role in the presence or induction of diapause in BWA across stands (Masaki 1961).

The observed overlapping cohorts may also be due to variation in the manifestation of these dormancies (Tobin et al. 2002, Bernardini and Di Russo 2004). For example, if only a proportion of individuals aestivate or diapause (i.e., facultative), others in the original cohort that do not enter a dormancy would continue developing and attain the adult stage at an earlier time. Variation in parental photoperiod, or the photoperiod during which the parent produces offspring, has also been shown to affect the presence and duration of early instar diapause in several insect species such as the blow fly (*Calliphora vicina* Robineau-Desvoidy) and Mormon cricket (*Anabrus simplex* Haldane) (Mcwatters and Saunders 1998, Srygley 2020) which may be contributing to the overlap of cohorts.

The presence of live individuals of all life stages in winter samples confirms that more than the crawler stage can successfully overwinter in northern Utah, differing from findings in previous studies conducted in eastern Canada (Balch 1952, Greenbank 1970). In New Brunswick, all life stages excluding the crawler have been observed dying by prolonged exposure to temperatures below 0°C and instantly below -20°C in a region of study where mean annual minimum temperatures ranged from -20 to -25°C (Greenbank 1970). The average minimum temperature across our study sites and years was slightly warmer (-19.16°C ± 1.13°C), though temperatures fell below 0°C for an annual average of 137 days (± 6.27). Winter survival may be enhanced by insulation provided by snowpack (Greenbank 1970), as the locations in this study receive substantial annual snowfall. Variation in thermal requirements of the different subspecies may also be a factor in these differences (Hensen et al. 2018). Additional research on a potential winter diapause in the BWA crawler life stage and cold tolerance thresholds for all life stages is needed to further understand the dynamics of life stage activity over winter in the Intermountain Region.

Management of BWA can involve removal of infested trees and targeted-tree insecticide applications (Johnson et al. 2005, Rideout et al. 2023) implemented during periods of crawler inactivity and activity, respectively. While this degree day model was developed using the BWA adult stage, the crawler was initially explored as the model life stage due to its dispersal capabilities and relevance in management action timing. However, the tendency for morphological similarity between settled crawlers and second instar nymphs (N2) (e.g., darkened color and inflated body) made distinguishing the two early instars challenging in field-collected bark samples. Uncertainty in the individual crawler and N2 counts encouraged the use of the adult stage for the DD model, though an alternate model approach could utilize unsettled (dispersing) crawler data.

In addition to challenges presented by life stage identification, annual improvements to the methodology of this study were incorporated. Sample storage in ethanol in 2020 removed the opportunity for accurate living status determination, though it ultimately supported the use of those 2020 datasets for evaluation of the 2021-2022 F2 model. Each 2020 evaluation dataset resulted in $R^2 \geq 0.92$, indicating that the 2020 sampling protocol – which included ethanol storage and lacked living status determination – was still effective at monitoring adult activity. While bark removal from several study sites as a form of sample collection provided ample sample sizes, it limited the ability to track development of individuals over time and therefore closely distinguish cohorts. The annual transition to new study trees presented an additional limitation to regularly monitoring individuals as well as potentially introducing a microclimate variable that could impact the life stage timing on different host trees. An alternative to this method of tracking BWA phenology may be to mark and monitor individual adelgids on a single host tree (Mitchell et al. 1961, McMullen and Skovsgaard 1972), though this method presents its own challenges and labor intensity.

Farmington Canyon, the first location confirmed to have BWA in Utah, was added as a study site in 2021 but removed in 2022 due to low populations and limited sampling ability. Upon initial discovery of BWA in Farmington Canyon in 2017, populations were very high, and fir damage in the area was assumed to be associated with the insect (Rideout et al. 2023). The apparent decrease in the presence of BWA in the area may be due to a density-dependent population trend in which the population fluctuates between an upper ceiling and a lower floor depending on factors such as resource availability or intraspecific competition (Stiling 1988). This trend has been observed extensively in forest insect populations and has been linked to potential mechanisms including host quality deterioration and increased diapause length (Tamburini et al. 2013). While more research on the presence of density-dependent population trends in BWA is critical, these mechanisms may serve an important role in the fluctuations and impacts of populations on Utah's subalpine fir forests.

Predicting Voltinism

Predicted thermal suitability for two generations of BWA trended slightly upward from 1980 to 2019 with several years at the lowest elevation site completing a partial third generation. Predictions of future voltinism indicated that in the next few decades there will be thermal suitability for two and no more than 2.5

generations except at Big Mountain Pass. Even using the RCP 8.5 climate projections, which represent a worst-case emissions scenario, three complete BWA generations are not predicted until near the end of the century. Moreover, predictions suggest that partial generations will occur at most sites throughout the century. While some herbivorous insects benefit from partial generations through increased overwintering populations, it is not clear what effect this cycle might have on BWA population success.

In some circumstances, accelerated development resulting in an additional generation may lead to population declines (Blackshaw and Esbjerg 2018). An important factor in determining success of an additional generation is whether it may reach the overwintering life stage before weather conditions deteriorate. In these cases, some species suffer demographically when additional generations are attempted but fail when seasons for completion are not long enough, a 'developmental trap' resulting from these new climate patterns (Van Dyck et al. 2015).

Furthermore, while it is experimentally unconfirmed that BWA in Utah experience periods of aestivation or diapause, an additional partial generation or an inconsistent second or third generation may lead to consequences related to dormancy. A general hypothesis is that predicted temperature increases between 1 and 5°C over the next 50-100 years could directly increase winter survival of many cold-adapted temperate species such as BWA (Bale and Hayward 2010). However, higher temperatures that result in faster development and facilitate a partial generation may also lead to asynchrony between diapause-sensitive life stages and critical photoperiods and thermoperiods for dormancy induction (Bale and Hayward 2010). Incomplete generations can also lead to a delay or deceleration in evolutionary adaptation related to dormancy in adverse conditions (Huang et al. 2007). Variations in thermoperiod, or the daily cycle of heat, that may be observed in the future have also been shown to affect the incidence of facultative diapause (Beck 1983, Tauber et al. 1986). Lengthened developmental seasons leading to a partial generation can drive additional asynchrony in development of insects and that of their host plants (Dixon 2003), though this pattern is more often present in insects that utilize flowering or otherwise highly seasonal plants. The ability for BWA to successfully overwinter in several life stages and the lack of required host phenology synchrony may provide resilience to the negative impacts of asynchrony.

In some historical and numerous future predictions, total annual DD exceeded the requirements observed for completion of two generations. Because no more than two generations were observed at the study locations, ranges of DD requirements for a third generation were estimated using those known for one and two generations, where an “upper” estimate used the assumption that a third generation would require DD similar to the first generation (i.e., less than the second), and a “lower” estimate assumed requirement similar to the second generation. This method of prediction inherently does not account for the possibility of changing DD requirements for any generation but provides a range of possible estimates of voltinism in a future climate of increasing temperatures. It is critical to recognize this uncertainty in combination with that inherently produced by climate modeling, despite the incorporation of projections from ten GCMs in this study.

Using this method, all future years are predicted to host at least a partial third, but fewer than 2.5, generation in which seasonality will inevitably be impacted.

Conclusion

Past research on BWA phenology occurred in coastal southern Canada, the eastern U.S., and the northwestern U.S. Although degree day models may be applied to large spatial scales, variations in regional phenology are well-known within BWA (Mitchell et al. 1961, Greenbank 1970, McMullen and Skovsgaard 1972), and a model developed for one region may not capture subtle differences in phenology for a different climatic region. This study is the first to present a degree day model for BWA, providing estimates for adult BWA timing in northern Utah that can inform timely management. Using this model, we show that thermal suitability for two BWA generations in northern Utah has increased slightly in the past 40 years with one and partial second generations predicted. Using the high emissions RCP 8.5 scenario, predictions for the next 40 years suggest continued increase in thermal suitability but only for a partial third generation (i.e., <2.5).

A better understanding of potential phenological disruptions that may occur from partial BWA generations and the impact on population success will be critical for continued development of dynamic management solutions. The model developed herein provides a tool for pest managers in northern Utah to predict the timing and occurrence of BWA generations given location-specific temperatures.

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Tables

Table II-1. Location information for balsam woolly adelgid phenology study sites, 2020-2022. All sites are located within the Uinta-Wasatch-Cache National Forest, Utah.

Site	Elevation (m)	Lat.	Lon.	County	Years Sampled
Green Canyon	2,039	41.804	-111.702	Cache	2020, 2021, 2022
Big Mountain Pass	2,274	40.829	-111.651	Salt Lake	2021, 2022
Laketown	2,326	41.725	-111.377	Rich	2020, 2021, 2022
Farmington Canyon	2,339	40.981	-111.809	Davis	2021
Rock Canyon	2,456	41.674	-111.41	Cache	2020, 2021, 2022

Table II-2. Coefficient of determination (R^2) values for predicting the lower developmental threshold (T_0) parameter combinations using DD_0 = 1 Jan and balsam woolly adelgid adult counts from all phenology study sites, 2021 and 2022.

T_0	R^2
0	0.7447
1	0.7396
2	0.7323
3	0.7226
4	0.7106
5	0.6959
6	0.6777
7	0.6562
8	0.6321
9	0.6062
10	0.5790

Table II-3. Degree day accumulation from 1 Jan (T_0 = 0°C) corresponding to the indicated cumulative percentage of completion of first- and second-generation adult balsam woolly adelgid at five northern Utah study sites, 2021-2022.

	Cumulative Percentage Completion					
Generation	5%	25%	50%	75%	95%	99%
F1	308	507	654	799	998	1,130
F2	1,284	1,755	2,058	2,333	2,683	2,900

Table II-4. Coefficient of determination (R^2) values showing strength of relationship between observed adult balsam woolly adelgid from evaluation datasets and those predicted by the first-generation (F1) and second-generation (F2) degree day models, developed using T_0 = 0°C and DD_0 = 1 Jan. *Dataset not used in model development.

		2020	2021	2022
F1	Green Canyon	—	—	0.9817
	Big Mountain Pass	—	—	0.9752
F2	Green Canyon	*0.9661	0.8560	0.9486
	Big Mountain Pass	—	0.8655	0.8943
	Laketown	*0.9787	0.8147	0.7799
	Farmington Canyon	—	0.8452	—
	Rock Canyon	*0.9153	0.9210	0.8640

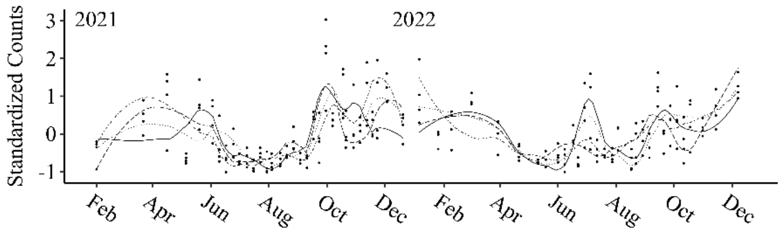
Table II-5. Predicted number of balsam woolly adelgid generations on subalpine fir at each site-year in northern Utah based on total annual degree days (DD) above 0°C and accumulated from 1 Jan. All study sites are located in northern Utah and were sampled from 2020 to 2022.

Site-year	Total DD	# of Generations
Green Canyon 2020	2,083	1.5
Green Canyon 2021	2,318	1.7
Green Canyon 2022	2,190	1.6
Big Mountain Pass 2021	2,734	1.9
Big Mountain Pass 2022	2,625	1.8
Laketown 2020	2,428	1.7
Laketown 2021	2,611	1.8
Laketown 2022	2,489	1.8
Farmington Canyon 2021	2,839	2.0
Rock Canyon 2020	2,100	1.6
Rock Canyon 2021	2,280	1.7
Rock Canyon 2022	2,209	1.6

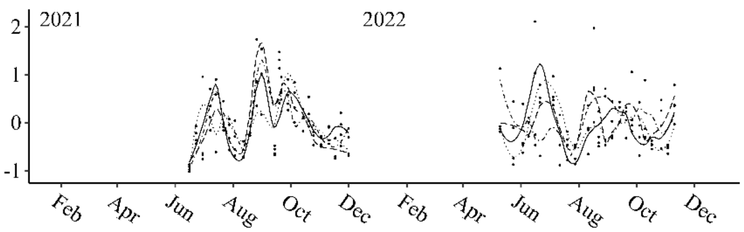
Figures

Figure II-1A-E. Z-score standardized counts for adult balsam woolly adelgid at five northern Utah study sites in the Uinta-Wasatch-Cache National Forest, 2021-2022.

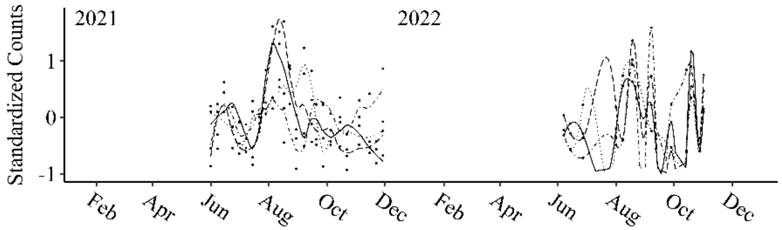
A. Green Canyon (elev. 2,039 m)



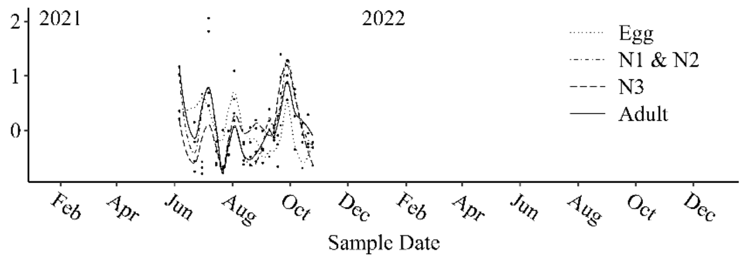
B. Big Mountain Pass (elev. 2,274 m)



C. Laketown (elev. 2,326 m)



D. Farmington Canyon (elev. 2,339 m)



E. Rock Canyon (elev. 2,456 m)

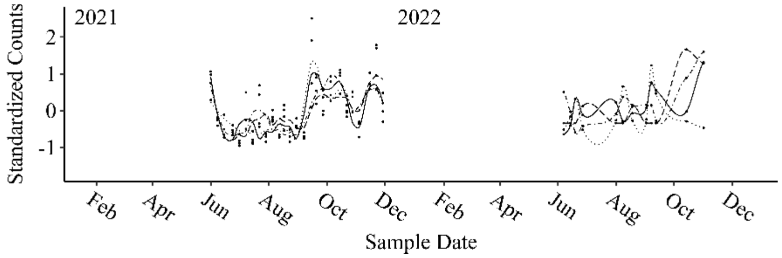


Figure II-2. Observed first- and second-generation adult balsam woolly adelgid cumulative proportions at five northern Utah study sites (2021 and 2022) and degree days (1 Jan biofix and lower developmental threshold of 0°C) fitted to cumulative Weibull distribution function.

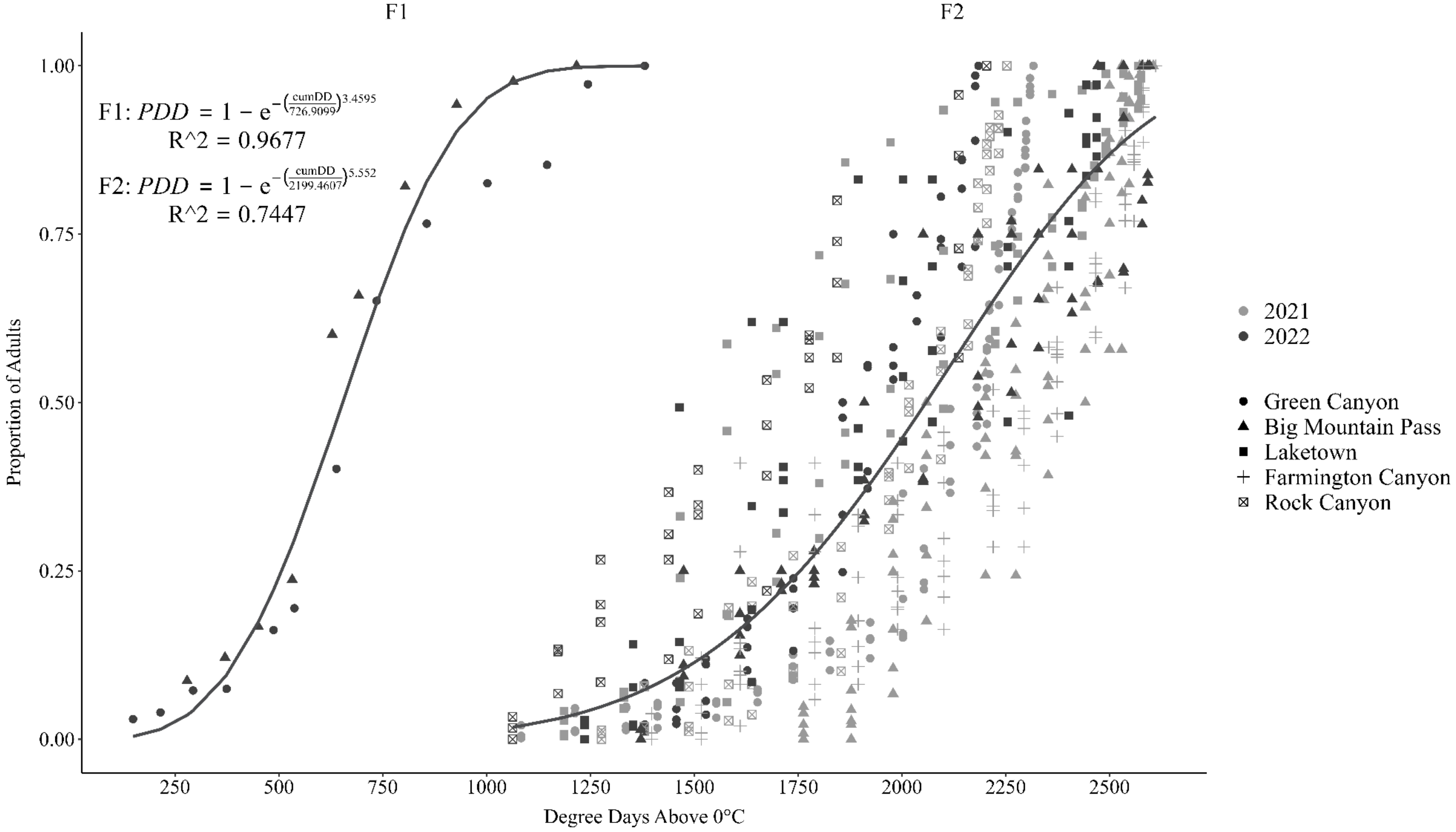


Figure II-3. Predicted annual generations of balsam woolly adelgid (BWA) at five northern Utah study sites in the Uinta-Wasatch-Cache National Forest from 1980 to 2019. Predictions below the dotted line were calculated using parameters estimated by a degree day model for BWA adults developed using observed data in 2021 and 2022. Those above the line were estimated with upper and lower feasibility boundaries, where an additional generation has degree day requirements similar to the first and second generations, respectively. Predictions for years above the dashed line are represented by a vertical range bar. A trend line using the LOESS method was fitted with a shaded 95% confidence interval.

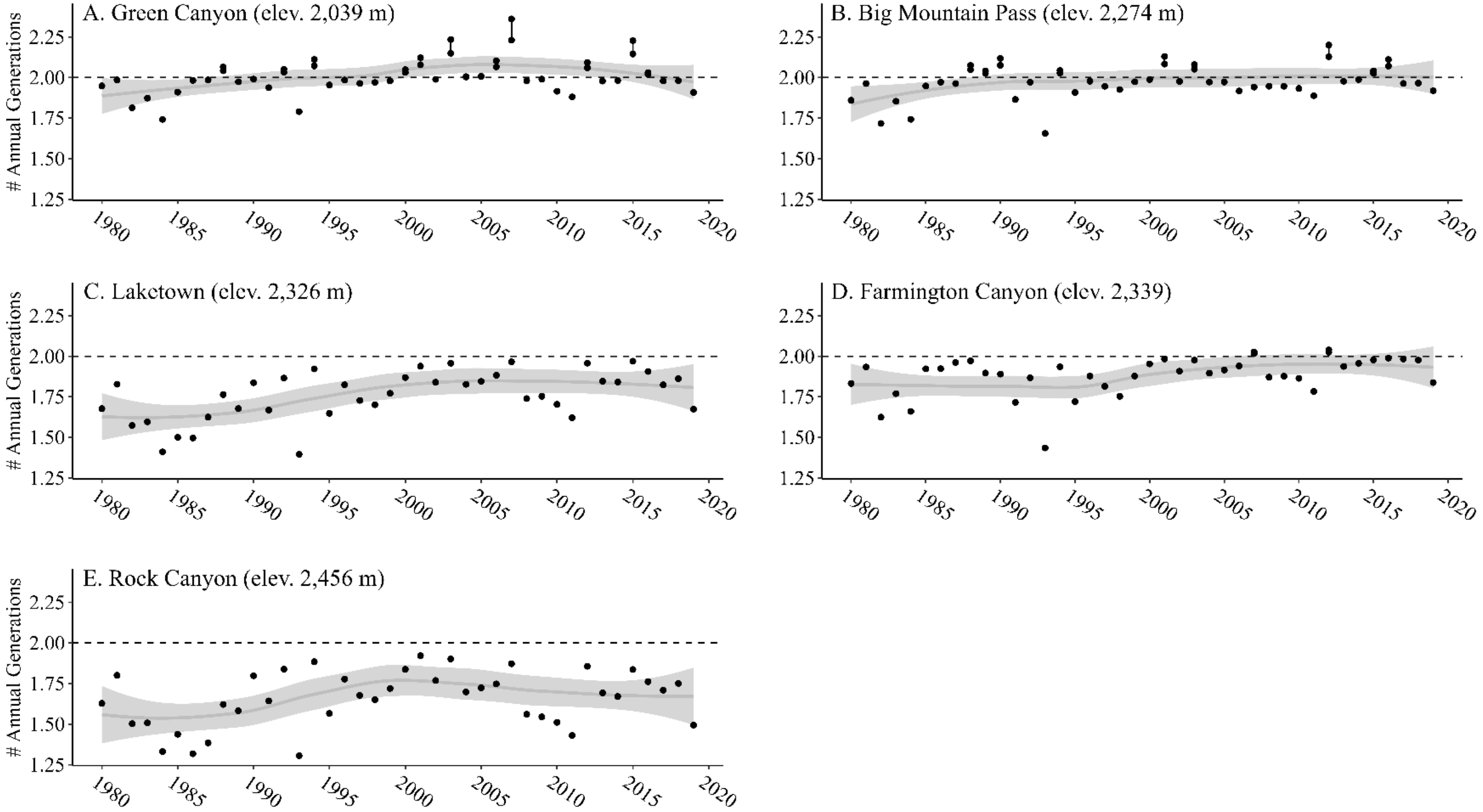
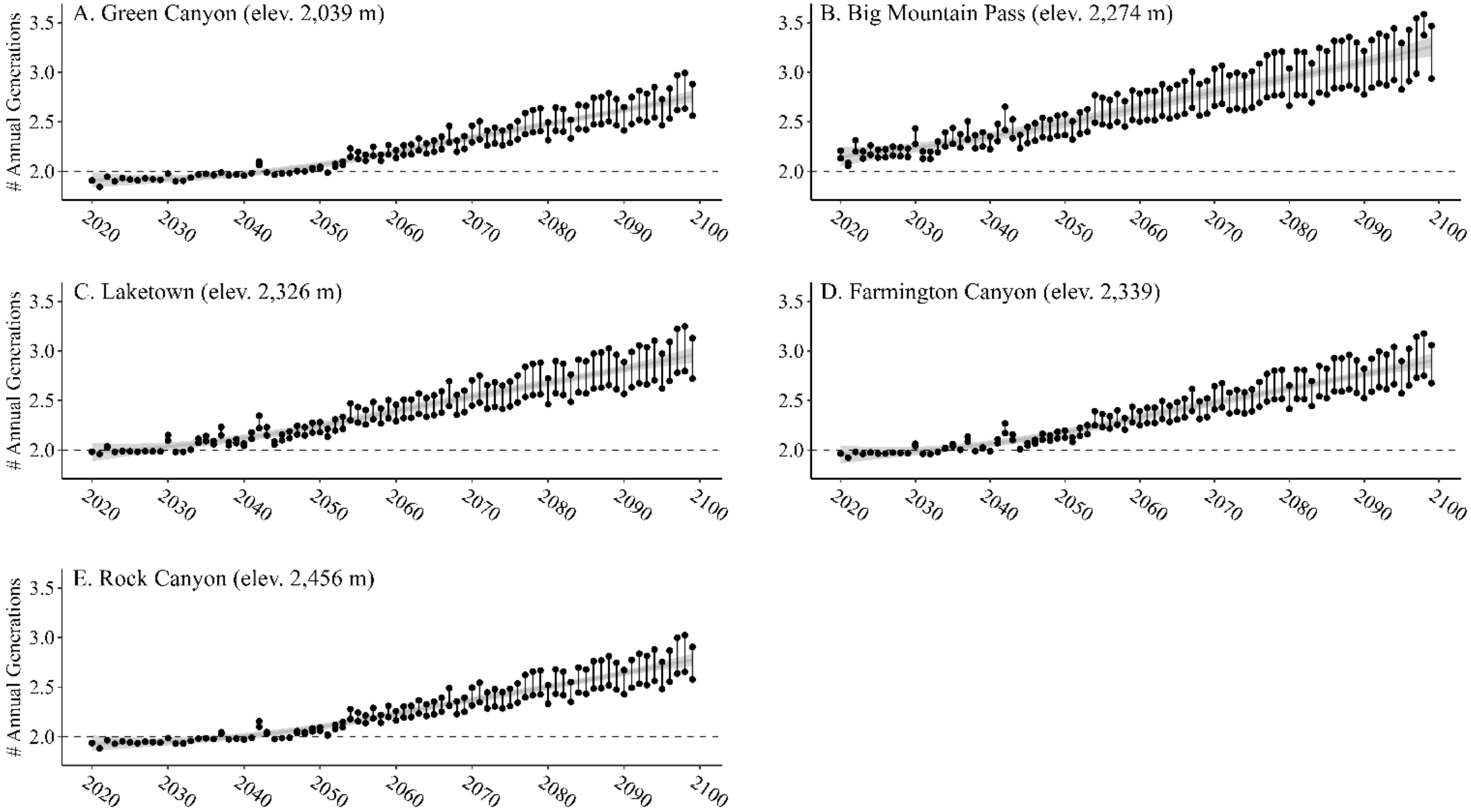


Figure II-4A-E. Predicted annual generations of balsam woolly adelgid (BWA) at five northern Utah study sites in the Uinta-Wasatch-Cache National Forest from 2020 to 2099. Predictions below the dotted line were calculated using parameters estimated by a degree day model for BWA adults developed using observed data in 2021 and 2022. Those above the line were estimated with lower and upper feasibility boundaries, where an additional generation has degree day requirements similar to the first and second generations, respectively. Predictions for years above the dashed line are represented by a vertical range bar. A trend line using the LOESS method was fitted with a shaded 95% confidence interval.



CHAPTER III

STICKY CARDS FOR MONITORING DISPERSING BALSAM WOOLLY ADELGID (HEMIPTERA: ADELGIDAE) CRAWLERS[2]

Abstract

The balsam woolly adelgid (BWA), *Adelges piceae* (Ratzeburg), is an invasive insect pest of true fir in North America native to south-central Europe. Since its range expansion into the U.S. Intermountain Region in the 1980s, BWA has caused significant mortality of subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.). The first nymphal instar, the crawler, is the only motile life stage and is therefore responsible for dispersal between host trees, usually by wind. Detection and monitoring of BWA populations for management decision-making is challenging because of the insect's small size and cryptic life stages. In this study, monitoring for dispersing crawlers using sticky cards was compared to a more labor-intensive bark sampling method with the goal of identifying a simplified, effective approach for crawler detection. The two sampling methods were compared in four northern Utah subalpine fir stands from Jun to Oct 2022. Sticky card orientation (horizontal or vertical) for optimal crawler capture and a mesh covering for bycatch reduction were tested. Sticky cards were effective in detecting dispersing crawlers, and counts tracked unsettled crawler densities observed on bark samples. Horizontal card placement with a mesh covering had higher crawler captures than vertical cards and reduced bycatch as compared to uncovered cards. Study results provide evidence that

sampling with mesh-covered sticky cards can be an effective monitoring tool for detection and monitoring of dispersing BWA unsettled crawlers and can support decision-making for optimal timing of BWA management tactics.

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[2] Coauthored by Diane G. Alston and Barbara J. Bentz

Invasion & Biology of BWA

The balsam woolly adelgid (BWA), *Adelges piceae* (Ratzeburg) (Hemiptera: Adelgidae), is an invasive forest insect native to south-central Europe (Havill et al. 2020). Likely imported to North America via infested nursery stock, BWA was first reported in Maine in 1908 with detections following in southeastern Canada and the eastern United States (U.S.) (Kotinsky 1916, Balch 1952, Speers 1958, Amman 1962, Havill et al. 2021). In the western U.S., BWA was first found in California in 1928 and Oregon in 1930 (Annand 1928, Keen 1952). Balsam woolly adelgid has since expanded its range into the Intermountain Region with first reports in Idaho in 1983 (Livingston and Dewey 1983) and Utah in 2017 (Rideout et al. 2023, Davis et al. 2020).

Balsam woolly adelgid utilizes its long stylets to feed through the bark into the outer bark tissue, or phellem, of true fir species (genus: *Abies*). Host species exhibit varying degrees of susceptibility to mortality by BWA with vulnerable species including Fraser fir (*A. fraseri* (Pursh) Poir.) and balsam fir (*A. balsamea* (L.) Mill.) in eastern North America and grand fir (*A. grandis* (Douglas ex D. Don) Lindl.), Pacific silver fir (*A. amabilis* (Douglas ex Loudon) Douglas ex Forbes), and subalpine fir (*A. lasiocarpa* (Hook.) Nutt.) in western North America. Other true fir species such as white fir (*A. concolor* (Gord. & Glend.) Lindl. ex Hildebr.) are reported as being attacked by BWA but exhibit low rates of mortality (Ragenovich and Mitchell 2006). Feeding by BWA typically leads to decreased photosynthesis and respiration in the tree, increased drought stress, and eventual tree death (Mitchell 1967, Puritch 1973, Cook et al. 2010).

Balsam woolly adelgid has three nymphal instars and is asexual in its introduced range in North America. The egg incubation period is roughly two weeks and is followed by development into the first instar, the "crawler". This is the only stage capable of motility and is roughly 0.4 mm in length (Fig. III-1A). Once hatched from the egg, crawlers may wander up to 30 m on the bark surface, probing for two hours to three days in search of a suitable feeding site (Balch 1952). During this unsettled period, crawlers may be passively dispersed among trees and across forested landscapes primarily by wind and occasionally by animals (Amman 1962, Woods and Atkins 1967, Atkins and Hall 1969). Upon choosing a feeding site, the crawler will insert its stylets and begin feeding on parenchyma cells. Crawlers then begin exuding wool-like strands of wax which continues throughout its nymphal development to the adult stage (Bryant 1974).

Current Approaches to Monitoring

Rapid and reliable detection of BWA has proved challenging due to the insect's small body size and cryptic nature. Detection on a tree typically occurs after the population has grown dense enough to form visible masses of wool on the tree bole or injury symptoms such as branch gouting are present (Bryant 1974, Arthur and Hain 1984, Mitchell and Buffam 2001, Overhulser et al. 2004, Hrinkevich et al. 2016). To support early detection and potential for intervention before severe injury occurs, development of a monitoring method for dispersing crawlers is critical to implementation of an integrated pest management (IPM) approach (Rideout et al. 2023).

Monitoring of BWA phenology has been achieved by tracking adelgid life stages on the tree bole using a field microscope, though this method is laborious and infeasible for most pest managers (Tunnock 1959, McMullen and Skovsgaard 1972). While still labor-intensive, another approach involves collection of infested bark samples followed by identification of BWA life stages in the laboratory (Mitchell et al. 1961). Targeted monitoring of dispersing crawlers of a BWA relative, the hemlock woolly adelgid (HWA) (*Adelges tsugae* Annand), has been achieved by placing sticky card traps underneath infested branches of host trees, *Tsuga canadensis* (L.) Carrière and *Tsuga caroliniana* Engelm. (Fidgen et al. 2020).

The objective of this study was to compare the efficacy of a novel BWA crawler monitoring method using sticky cards with a bark sampling protocol to assess parallels in the detection and seasonal tracking of dispersing crawlers. If successful, a sticky card protocol could be more convenient, cost-effective, and likely to be adopted by forest managers to support early pest detection and treatment decision-making.

Monitoring Methods

Study Sites

This study was conducted from 16 Jun to 14 Oct 2022 in four mixed conifer stands composed primarily of subalpine fir and secondarily of Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), white fir, and the deciduous quaking aspen (*Populus* *tremuloides* Michx.). Study sites ranged in elevation from 2,039 to 2,456 m and were located within the Uinta-Wasatch-Cache National Forest in northern Utah (Table III-1).

Bark Samples

On a weekly basis, one 6.45 cm^2 (1 in^2) piece of bark was removed from each of four BWA-infested subalpine fir trees at each site using a 2.54 cm (1 in) width wood chisel (DeWalt Industrial Tool Company, Towson, MD, USA). Bark samples were collected from the north aspect of each tree at 1 m height above the base. Samples were placed in individual 50 mL centrifuge vials (VWR International, Radnor, PA, USA) for transport to the USDA Forest Service Rocky Mountain Research Station in Logan, Utah.

In the laboratory, bark samples were placed in a 35 mm glass petri dish (Thermo Fisher Scientific, Waltham, MA, USA) and BWA life stages (egg, 1st - 3rd instars, adult) were enumerated based on morphology described by Balch (1952) with the aid of a stereomicroscope (25× magnification) (Fig. III-1B). To remove adelgids that adhered to the sides of the centrifuge tube, the tube was rinsed with distilled water and poured into a 35 mm glass petri dish. Adelgids in the rinse water were counted and included in sample count totals. Samples were processed within two hours of collection or stored in the refrigerator at 5°C and processed within three days. If the latter occurred, the sample was allowed time to warm to room temperature before processing.

To determine if adelgids were alive upon collection, the following process developed by Mech et al. (2018) for HWA was used: gently remove adelgid from the bark tissue and observe for stylets reinsertion attempts or body movement for 15 seconds, and if no stylets or body movement was observed, the adelgid was pierced for observation of hemolymph viscosity and color. If body or stylets movement was observed or hemolymph was fluid and deep red-purple in color, the adelgid was determined to be alive. If there was no movement and the hemolymph was dry or tacky, the adelgid was determined to be dead. For adelgids counted in the sample wash solution, the body was pierced to observe exuding hemolymph for appropriate viscosity and color.

Sticky Card Samples

One-sided yellow sticky cards (23 x 14 cm; Alpha Scents Inc., Canby, OR, USA) with grid squares the same size as bark samples (6.45 cm^2; 35 squares per card) were deployed and collected at each study site on bark sampling dates. Cards were deployed first at the Big Mountain Pass site on 16 Jun and at other sites on 8 Jul. All cards were collected for the final time during the week of 10 Oct. Wooden stakes (2 cm width by 1 m height) were placed 10 cm deep on the north side of each of the four study trees at 60 cm distance from the tree bole.

Two card orientations were tested from 16 to 28 Jun: 1) horizontal with the card attached by a tack on top of the stake (92 cm above the ground) with sticky side up; and 2) vertical with the card placed 6 cm below the horizontal card on the side of the stake facing the study tree (Fig. III-2A). Based on preliminary results, all cards were deployed only in the horizontal orientation beginning in July. Upon retrieval of cards, plastic cling wrap was stretched across the tacky side of each card to protect BWA caught in the adhesive during transportation.

On the week of 29 Aug, increasing invertebrate (insect and arachnid) and vertebrate (bird and bat) bycatch began occurring on the cards. To reduce bycatch, a fine polyethylene mesh screen (1 mm opening; Army Surplus Warehouse, Idaho Falls, ID) was cut to the same size as the sticky card and stapled on the tacky side of each card (Fig. III-2B). Resulting observations showed that the mesh-covered cards captured less bycatch and provided greater ease of card handling during placement and retrieval. All cards were deployed with mesh covers beginning the week of 5 Sep through termination of sampling on 14 Oct.

Cards were stored in the refrigerator at 5°C for up to two weeks until BWA life stages were counted under a stereomicroscope (25× magnification). For cards with estimates of more than 500 crawlers, seven squares (6.45 cm^2) were randomly selected for counting and counts increased by five times to reflect an estimate of the entire card surface. All adelgids found on sticky cards were counted due to the tacky adhesive on cards making living status assessment challenging.

Results & Discussion

Across the card orientation comparison period, horizontally positioned cards had higher mean crawler captures (17.89 ± 9.39, n = 9) than those with vertical orientation (1.17 ± 1.17, n = 6). Remaining results are therefore presented only for horizontal cards.

Due to card loss from weather or bycatch and methodological miscommunication resulting in three missing weeks in July, the total sampling time frame of viable horizontal card samples and bark samples was 14 weeks. Analysis of sampling methods included all crawlers (alive and dead) due to the challenge of living status determination on card samples. Across all study sites during this period, the average sticky card square (6.45 cm^2) detected 1.52 times the number of crawlers as bark samples (6.45 cm^2). Sticky cards captured three non-crawler life stages on 46 cards representing all sites (218 eggs, 1 second instar, 2 adults) during this sampling period.

Peak summer crawler abundance is expected in late Jun (Mitchell et al. 1961), though in the first sampling interval that cards were deployed (16-21 Jun), crawlers were detected only on sticky cards and not on bark samples. Conversely, crawler abundance is assumed to be low in Sep and Oct when development to adulthood is occurring. While crawlers were detected in both sampling methods during this period, considerably more crawlers were detected on sticky cards than on bark samples. The earlier detection of crawlers and higher densities found on sticky cards supports the utility of this monitoring method for BWA detection in the peak season as well as when population sizes are low.

Following peak abundance in Jun, the crawlers are suspected of entering a summer aestivation period lasting for several weeks through Jul and Aug (see

Chapter II). It's during this period that the majority of the population is presumably composed entirely of non-developing crawlers, a pattern which is represented by steady crawler counts from both sampling methods in the month of Aug (Fig. III-3). Additionally, alignment of crawler population peaks and troughs in weekly samples for both methods indicate that sticky cards were effective for monitoring crawler activity over time (Fig. III-3). Sticky cards may therefore be useful for inferring crawler life stage timing and when deployed for the entire growing season, may be an effective tool to support the study of BWA phenology.

In this study, microscope magnification of 25× was required for bark sample processing due to debris and adelgid wool present on the bark. In contrast, a hand lens (commonly between 10× and 25× magnification) may be suitable for processing mesh-covered sticky cards, providing greater accessibility for pest managers. Sample processing time for bark samples averaged 45 min per sample to count all life stages, whereas the average time to count crawlers on sticky cards without mesh was 25 min and 15 min for cards with mesh due to reduction in bycatch and debris. Additionally, the card adhesive allowed for longer-term storage in the refrigerator post-sampling than bark samples, which when stored for more than several days, introduced the risk of mold growth and subsequent specimen damage. This feature of sticky card traps allows for more flexibility in sample processing by the pest manager.

A notable drawback of bark sampling is the destruction to the host tree's outer bark and phloem, both crucial components for protection and food transportation. The cambium layer, which produces a significant number of xylem cells that are critical for water and nutrient transportation from the soil throughout the tree, may also be negatively impacted by bark sample removal (Jožica et al. 2009). Conversely, deploying sticky cards does not impact tree health, though card damage or loss during deployment due to precipitation and wind did occur in this study. Wildlife and human activity may also be potential impacts of this method. These concerns may be mitigated by greater frequency in card retrieval and selection of monitoring sites with lower likelihood of disturbance.

Applications in IPM Programs

Current management practices for BWA include selective removal of infested trees when crawlers are inactive and targeted-tree applications of an insecticide during periods of crawler activity (Johnson et al. 2005, Rideout et al. 2023). The targeted nature of sticky card traps for detecting dispersing BWA crawlers while being low in time- and labor-intensity and highly accessible to land managers for purchase at minimal cost suggests that cards can be a valuable tool to inform timing of management practices by homeowners and forest managers. Deploying horizontal mesh-covered sticky cards is an efficient monitoring strategy for dispersing BWA crawlers that can be implemented to inform timely management tactics including tree removal or insecticide sprays. Alongside a phenology tool such as a degree day model, this strategy may help to reduce the negative impacts caused by BWA on forest stand health.

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Tables

Table III-1. Study site descriptions for balsam woolly adelgid crawler monitoring in the Uinta-Wasatch-Cache National Forest in northern Utah, 2022 (ordered from lowest to highest elevation).

Site	Elevation (m)	County	Latitude	Longitude
Green Canyon	2039	Cache	41.80404	-111.70213
Big Mountain Pass	2274	Salt Lake	40.82903	-111.65133
Laketown	2326	Rich	41.72479	-111.37652
Rock Canyon	2456	Cache	41.67355	-111.41008

Figures

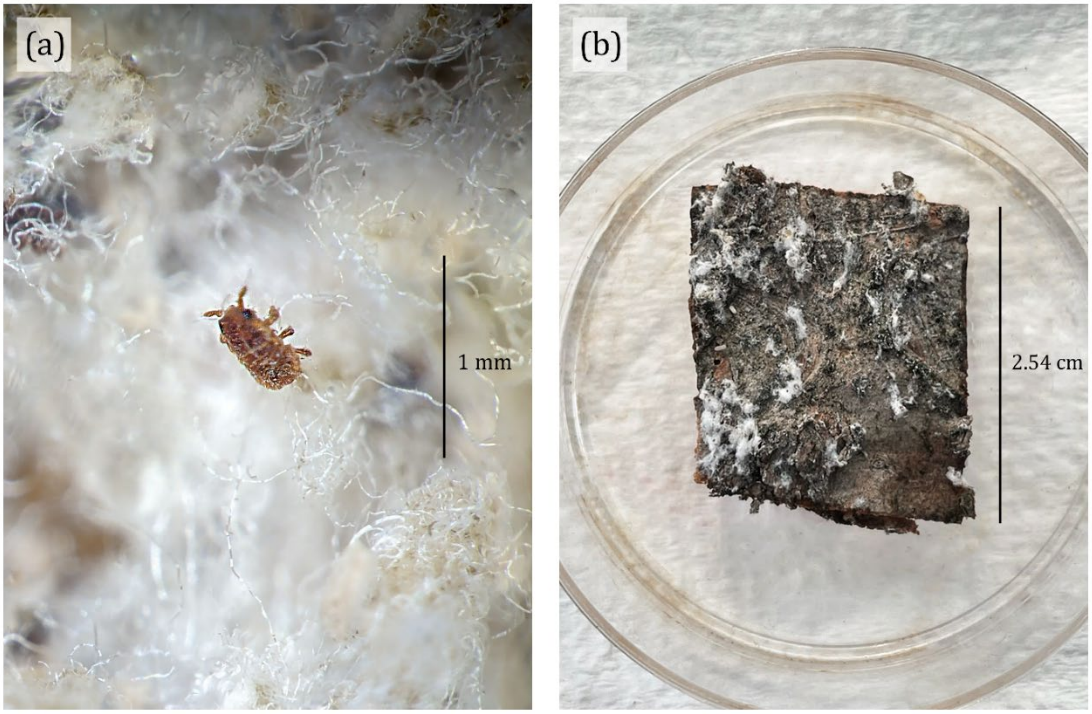

Figure III-1A-B. (a) Unsettled balsam woolly adelgid crawler (approx. 0.4 mm in length) on wool-covered bark sample. (b) Balsam woolly adelgid-infested subalpine fir bark sample (6.45 cm^2) with visible adelgid-produced white, woolly masses.

Figure III-2A-B. (a) Horizontal and vertical orientations of sticky cards tested for efficacy of capturing dispersing balsam woolly adelgid crawlers. More crawlers were detected on cards in the horizontal orientation. (b) Polyethylene mesh (1 mm opening) was added to the sticky cards to reduce bycatch while monitoring for balsam woolly adelgid crawlers. Mesh-covered cards resulted in reduced bycatch, sustained crawler captures, and increased handling ease when compared to cards without mesh.

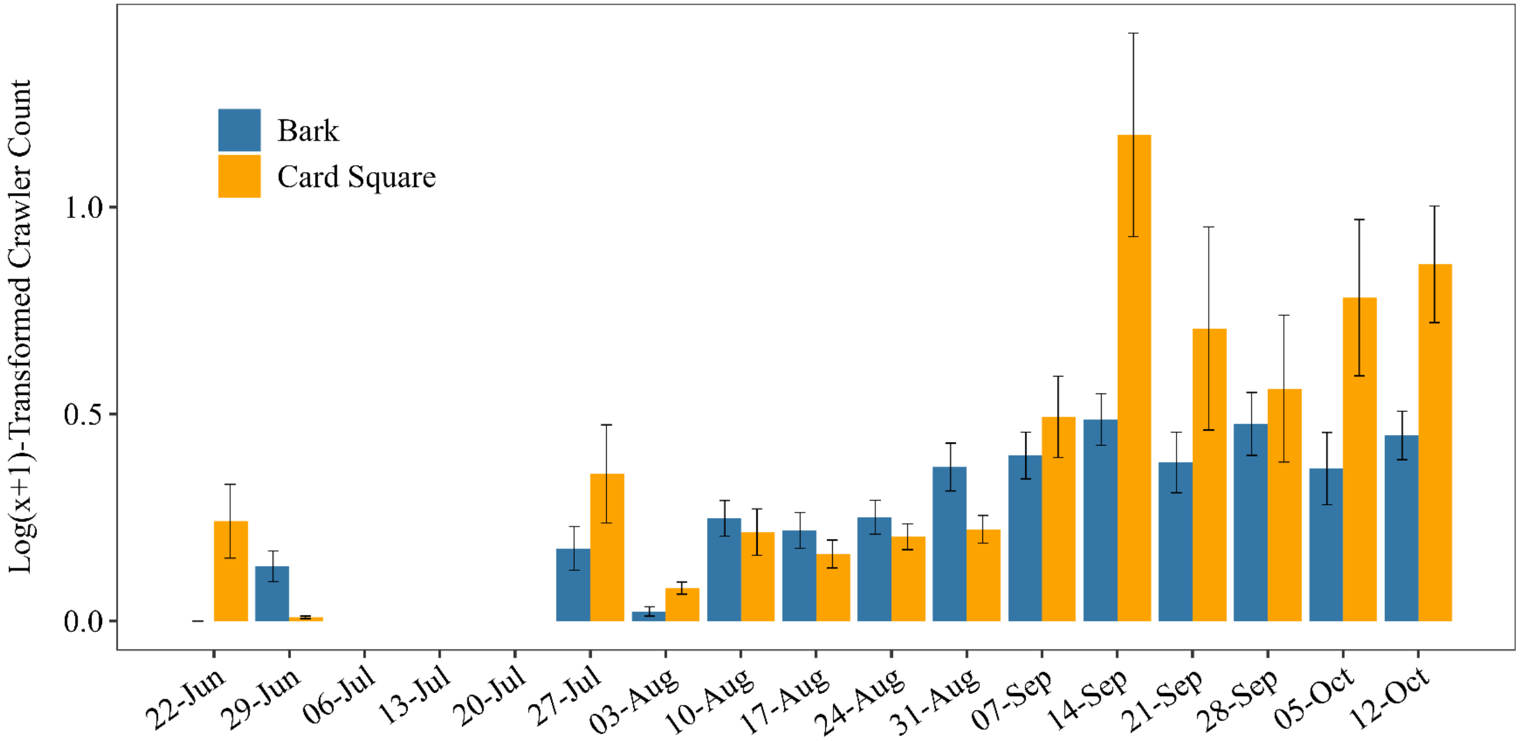

Figure III-3. Weekly log-transformed means (± SE) of balsam woolly adelgid crawler counts for bark (6.45 cm^2) and sticky card (one square; 6.45 cm^2) sampling methods at four forest sites in the Uinta-Wasatch-Cache National Forest in northern Utah, 16 Jun to 14 Oct 2022. Counts were summed across trees and sites per week then log(x+1)-transformed. Data loss resulting in missing weeks in Jul were due to incorrect data collection. Error bars represent variation in means across the four sites each week. A mesh screen was attached to all cards beginning 5 September to reduce bycatch.

CHAPTER IV

SUMMARY AND CONCLUSIONS

The current knowledge on balsam woolly adelgid (BWA) phenology in its invasive North American range is primarily founded on studies conducted in climatic zones and geographic regions different than that of Utah. The studies herein have explored multiple potential tools for use in biologically-based management of BWA in northern Utah's subalpine fir forests. The exploration of critical baseline knowledge including general phenology, voltinism modeling, and a monitoring strategy that targets the motile crawler life stage creates a strong foundation for informing timely management of BWA as well as supporting continued research on this invasive pest in Utah.

In Chapter II, systematic sampling of BWA was conducted across five subalpine fir stands within the Uinta-Wasatch-Cache National Forest. This sampling provided data on BWA life stage timing and relative abundances throughout the year across a range of elevations. Individuals of all BWA life stages were found on bark samples from most sample dates, indicating the presence of overlapping cohorts. While this can make estimating generation number and timing challenging, in most cases, one or two life stages dominated at a time while others were less common. Two peaks in adult counts were evident at all study sites, with the first occurring in early summer and the second between late summer and early fall, indicating the presence of two annual generations. Within this bivoltine life cycle, potential support was provided for a summer dormancy as well as evidence of winter survival of life stages other than the crawler. These novel discoveries provide valuable information for pest managers interested in tracking or targeting the adult stage for management action.

In this chapter, air temperatures recorded at each study site and weekly to monthly sampling contributed to the development of a phenology model for predicting generation timing and proportional progression of the adult life stage through each generation. In this degree day model, these proportional data were fitted to the cumulative Weibull distribution to estimate when adult peaks can be expected for a given year and location in northern Utah based on temperature. Degree day models incorporate the lowest temperature at which development in a species can occur, called the lower developmental threshold (LDT). Because this information has not been determined experimentally for BWA, the degree day model was developed for a range of LDT (0-10°C) when accumulating from 1 Jan. The model was optimized using a LDT of 0°C, which may serve as an important baseline for future phenological research on BWA. Using the parameters estimated by this degree day model, pest managers will be able to input location-specific weather station data to estimate BWA generation number (voltinism) and timing for a given infested fir stand.

This degree day model for predicting current voltinism in northern Utah was then expanded to estimate historical (1980-2019) and future voltinism (2020-2099) at the study sites. Using BioSIM-generated historical data, it was estimated that there has been increasing thermal suitability at all study sites for completion of two generations, though only the two lowest elevation sites regularly hosted two complete, or nearly complete, generations.

Forecasts for 2020-2099 were estimated using future climate data generated from the Multivariate Adapted Constructed Analogs (MACAv2) downscaled climate model dataset. These climate projections follow the trajectory of Representative Concentration Pathway (RCP) 8.5, the highest and worst-case emission and climate warming scenario. Using observed requirements for completion of one and two generations, predictions were made for requirements of an additional generation. In this climate future, the model forecasted that BWA can be expected to hover around two complete generations in the next two to four decades. The lack of necessity for changes or increases in management action frequency of BWA may be good news to pest managers, though increasing thermal suitability for three generations by 2099 at all sites was also predicted. The method employed for voltinism forecasting in this chapter included a technique in BWA research that uses current life cycle requirements to make future assumptions. While the use of current-climate degree day modeling for forecasting is common, this technique is limited to current observational data. The exploration of a unique approach to forecasting unknown future scenarios based current data (i.e., predictions for additional generations not observed in the current climate) in this research may provide a useful baseline for further research on voltinism forecasting. In addition, these predictions will be useful for dynamic future decision-making in forest management regarding BWA.

In Chapter III, sticky cards were explored for use in monitoring the wind-dispersing BWA crawler (1st instar) life stage. Sticky cards were deployed to coincide with weekly bark sampling from Jun to Oct 2022. Comparisons included card orientation and the addition of mesh covering to reduce bycatch. Horizontally-positioned cards captured considerably higher crawlers than vertically-oriented cards. The addition of a fine polyethylene mesh was found to reduce invertebrate and vertebrate bycatch on cards. Not only did the mesh-covered cards result in substantially less bycatch, but they also provided greater ease of handling during retrieval and more efficient processing. Fluctuations in the crawler counts observed on sticky cards aligned with those observed in the associated weekly bark samples, indicating potential utility of sticky cards as seasonal monitoring tools for the dispersing BWA crawler life stage. Overall, this study provides evidence for the utility of an accessible approach for pest managers to monitor and target the motile crawler stage to support implementation of integrated pest management tactics.

An important component of this research has been the outreach opportunities offered through Utah State University (USU) Extension. Balsam woolly adelgid is relatively new to the Intermountain Region, and through this research, we have learned about the insect’s life history and voltinism in northern Utah. To support dissemination of updated pest biology and management information, an existing USU Extension fact sheet was revised to include regional BWA life history and phenology, and a bivoltine life cycle graphic created by the USU Extension graphic artist (Appendix B). Additionally, two articles on BWA were published in Utah Pests Quarterly, a newsletter that is disseminated broadly to USU Extension and the public (currently 12,680 subscribers). This article provided updates on BWA in Utah to forest managers, homeowners, and other stakeholders such as ski resort operators (Appendix C). In addition to the written products presented herein, numerous presentations at events including conferences, workshops, and field days have supported the distribution of general information about BWA to broad audiences. These resources provided essential public awareness and understanding of the impacts and potential tools for supporting sustainable management of BWA.

APPENDICES

APPENDIX A

AUTHORSHIP AND CITATION OF CHAPTERS

Chapter II:

This is an author-produced version of an article intended for publication by the Journal of Economic Entomology.

Chapter III:

This is an author-produced version of an article intended for publication by the Journal of IPM.

APPENDIX B

BALSAM WOOLLY ADELGID (FACT SHEET)

UTAH PESTS fact sheet
Extension UtahStateUniversity

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Balsam Woolly Adelgid

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Quick Facts

- Balsam woolly adelgid (BWA) was first detected in the U.S. in 1908. It now infests true firs along both U.S. coasts and in several Interior West states.
- BWA was first observed killing subalpine fir trees in northern Utah forests in 2017 and is now confirmed in 10 counties.
- Due to its small size, its presence is difficult to detect until a tree is heavily infested and displays advanced symptoms (canopy decline, branch and node swelling).
- Controlling BWA with insecticides in forested landscapes is limited by high cost and other factors. The most viable management option is removing infested trees.
- BWA on individual or small groups of trees can be managed with insecticides applied during late spring/early summer and fall when the crawler (juvenile) stage is active.

The balsam woolly adelgid (BWA), *Adelges piceae* (Ratzeburg) (Hemiptera: Adelgidae), is a tiny sap-sucking insect that was introduced to North America from Europe (Fig. 1). In the U.S., it is a pest of true firs along both U.S. coasts and in several Interior West states, where it impacts the health of firs in forested habitats, Christmas tree production, and potentially urban areas.

Fig. 1. *Balsam Wooly Adelgid Female Adult*

Fig. 2. *Subalpine Fir Stand in Farmington Canyon, UT, Infested With Balsam Woolly Adelgid*

In some areas of the U.S., BWA has devastated fir populations in both forests and Christmas tree farms. In Utah, subalpine fir (*Abies lasiocarpa*) is a highly susceptible host tree. White fir (*A. concolor*) is also a host but is more tolerant. Douglas fir (*Pseudotsuga menzisii*) is not a true fir and, therefore, is not affected by BWA. The USDA Forest Service Forest Health Protection (FHP) team in Ogden first detected and confirmed BWA in 2017 in Farmington Canyon (Fig. 2) and near Powder Mountain Ski Resort. It is now confirmed in Box Elder, Cache, Rich, Weber, Morgan, Davis, Summit, Salt Lake, Wasatch, and Utah counties. Subalpine fir can typically be found at elevations of 5,900–11,400 feet (1,798–3,475 m) and often cohabitate with species such as white fir, Engelmann spruce (*Picea engelmannii*), and quaking aspen (*Populus tremuloides*).

TREE INJURY AND SYMPTOMS

Subalpine fir is at high risk for BWA attack in Utah. Mature trees, 4 inches (10 cm) or more in diameter, seem most susceptible, but saplings may also be affected. In the West, stem (trunk) infestations are common at sites with higher-quality soils and lower elevations. Crown attacks occur more often at sites with poorer soils and higher elevations. Damage is most severe during the first decade of infestation in an area. It is unclear how long BWA may persist in an affected habitat, though pest impacts will remain indefinitely. BWA is most visible in the fall in Utah. Common tree symptoms include:

- Yellowing, then bronzing, of needles on the inner branches that remain attached to the tree branch (called branch flagging) (Fig. 3).
- Loss of apical dominance (curling outward of crown branches called top curl, or general upper crown death) (Fig. 3).
- Reduced growth, stunted trees/branches, particularly in saplings (Fig. 4).
- Woolly material evident on tree bole near the tree base (Fig. 5).
- Abnormal swelling of branch nodes and buds called "gouting" in response to adelgid feeding (Fig. 6).
- Reduced cone production and poor stand regeneration.

Fig. 3. *Fraser Fir Christmas Tree Exhibiting Branch Flagging and Loss of Apical Dominance*

Fig. 4. *Young Subalpine Fir Infested With Balsam Woolly Adelgid Exhibiting Severely Stunted Growth*

Stem or bole infestations tend to be more serious than crown infestations. Infestation can also result in wide, irregular growth rings and reddish, brittle wood called "rotholz," though this symptom has not been observed in the Intermountain West. Host responses to BWA feeding eventually cause decreased water flow to the crown, leading to drought-like symptoms and eventual tree death. Tree mortality typically occurs within 2-10 years of infestation, but heavy infestations can kill trees in 2-3 years.

Fig. 5. *White Woolly Masses of Balsam Woolly Adelgid on a Fir Tree Stem Base*

Fig. 6. *Abnormal Swelling, or Gouting, of Fir Branches from Balsam Woolly Adelgid Feeding Injury*

LIFE HISTORY

In its native range, BWA utilzes both spruce and fir species for different parts of its life cycle. However, in North America, BWA only utilizes true firs as its European spruce host is not present. BWA populations in North America are composed of only females reproducing without mating (parthenogenesis), because sexual reproduction requires the European spruce host. Depending on host species and climate, between two and four generations are typically observed in western North America, and two have been observed in northern Utah (Fig. 7).

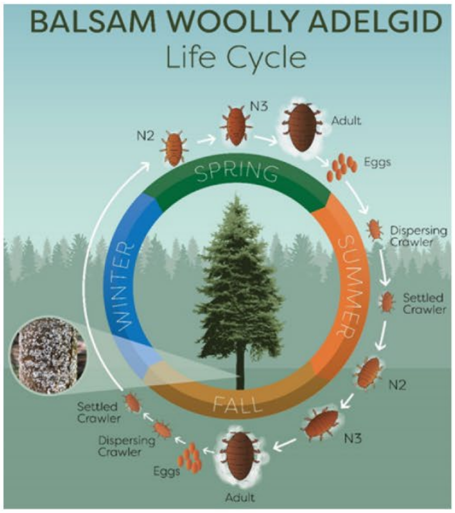

Fig. 7. *Balsam Woolly Adelgid Life Cycle in Utah With Two Generations*

The egg incubation period is roughly 2 weeks and is followed by development into the first instar, the "crawler." This is the only stage capable of motility and is roughly 0.4 mm in length (Fig. 8). Once hatched from the egg, crawlers wander the bark in search of a suitable feeding site. During this unsettled period, crawlers may be passively dispersed among trees and across forested landscapes primarily by wind and occasionally by animals. Upon choosing a feeding site, the crawler will insert its stylet and begin feeding.

Fig. 8. *Balsam Woolly Adelgid Crawler (Juvenile) on a Woolly Mass*

Fig. 9. *Female Adult Balsam Woolly Adelgid (left) With Eggs (right)*

MONITORING

Rapid and reliable detection of BWA has proved challenging due to the insect's small body size and immobile nature. Detection on a tree typically occurs after the population has grown dense enough to form visible masses of wool on the tree bole (Fig. 10) or injury symptoms such as branch gouting are present.

Fig. 10. *Dense Visible Masses of Balsam Woolly Adelgid Wool on a Subalpine Tree Bole*

One detection method is regularly removing bark pieces followed by viewing under a dissecting microscope or high-powered hand lens (Fig. 11). This approach can be effective but is time consuming, requires specific equipment, and may be harmful to the tree's bark over time.

Fig. 11. *Bark Sample From a Balsam Woolly Adelgid Infested Tree*

Targeted monitoring of dispersing BWA crawlers using sticky cards has shown potential for being a simple and accessible monitoring tool for tracking the timing of crawler dispersal and potentially population densities. Dispersing crawlers may be detected by placing sticky cards horizontally (sticky side facing up) on a stake or post below the canopy of the infested tree. To reduce bycatch, attach a fine mesh screen to the card before deploying on the stake (Fig. 12). For the greatest reduction in bycatch, the mesh screen should have openings between 1 mm and 1 cm. Cards should be regularly removed, replaced, and inspected for crawlers using a hand lens. Placing these cards near fir trees between April-June and August-September can provide location-specific valuable insight into timing management actions with periods of crawler dispersal.

MANAGEMENT

Cultural Control

Completely removing BWA from western ecosystems is unrealistic as they are widespread and disperse by wind. At the forest scale, the most effective tactics to reduce BWA damage include:

- Selectively removing heavily infested trees in winter when crawlers are inactive.
- Considering prevailing winds when establishing cutting boundaries.
- Growing fir on short rotation cycles.
- Favoring nonhost tree species and genetically resistant strains or hybrids through selective harvesting and planting.
- Using stand management techniques to promote stand vigor.
- Limiting the movement of infested firewood.

Fig. 12. *Yellow Sticky Card Trap With Fine Mesh*

Several hazard/risk rating systems have been developed for forest managers to optimize scouting and management programs for BWA (Ragenovich & Mitchell 2006; Hrinkevich et al., 2016). Fir species, site elevation, and soil/stand conditions are the primary factors driving stand susceptibility. Adding to the challenge of managing this insect is the lack of market value for subalpine fir; recovering treatment costs through selling sawlogs is, therefore, infeasible.

Biological Control

Thirty-three predator species have been released and monitored for establishment and effectiveness at BWA management between 1933 and 1969. Of these, six species successfully established in both the U.S. and Canada: three fly species (families: Chamaemyiidae and Cecidomyiidae) and three beetle species (families: Coccinelidae and Derodontidae). Despite establishment and evidence of predation on BWA, there have been no confirmed reductions in BWA populations or decreases in tree mortality associated with any of these biological control agents.

Chemical Control

Due to their small size, protected feeding sites, and waxy coatings, aerial insecticide applications do not provide coverage adequate for large-scale insect control. A thorough insecticide application to high-value trees using a high-pressure system can provide BWA control in areas such as ski resorts, cabin properties, campgrounds,

Table 1. *Insecticides for Balsam Woolly Adelgid Control*

Commercial	
IRCA Mode of Action Groups	**Insecticide**
Carbamate (group 1A)	Carbaryl
Neonicotinoid (group 4A)	Dinotefuran Thiamethoxam
Organophosphate (group 1B)	Chlorpyrifos*
Pyrethroid (group 3A)	Bifenthrin Esfenvalerate
Tetronic & tetramic acid derivatives (group 23)	Spirotetramat
Homeowner	
IRCA Mode of Action Groups	**Insecticide**
Neonicotinoid (group 4A)	Imidacloprid
Pyrethroid (group 3A)	Permethrin
Potassium salts of fatty acids; petroleum distillate	Insecticidal soap/oil
Sucrose esters	Sucrose octanoate

*Requires a Utah pesticide applicator license to purchase and apply.

tree farms, and urban settings. Chemical treatments can provide useful when combined with other management techniques, such as nonhost tree planting, but alone would be indefinite, costly, and ongoing.

For Utah, the current recommendation is to target crawlers with a residual insecticide, horticultural oil, or soap in summer and/or fall. Specific timing of application to infested trees will depend on temperature, elevation, and location. To appropriately time insecticide applications, monitor for the crawler stage in late spring/ early summer and/or fall. Timing applications to coincide with peak crawler activity is more important when using soaps or oils compared to longer-residual chemicals like the pyrethroids. Be aware of plant injury associated with soap or oil application before deciding to apply one of these tools. Table 1 displays available insecticide control options.

Using systemic neonicotinoids may provide control of BWA; however, this has not been confirmed by research. Systemic neonicotinoids are transported through the sapwood via water uptake. Moderate to severe damage from BWA will reduce water flow within the tree, limiting efficacy. If found effective, systemic neonicotinoids would be best used for new to moderate infestations, or preventively if infested trees are nearby and spread is anticipated.

IMPLICATIONS FOR FOREST HEALTH

Widespread mortality of subalpine fir is already occurring at some locations in northern Utah. In many cases, there are few other tree species to occupy the growing site. This problem increases the potential for BWA to inflict great ecological damage through increased erosion, decline in watershed health, loss of wildlife and their habitat, and reduction in recreational value. Additionally, potential dying and dead fir adding to fuel loading in forest landscapes is a high concern. True fir species are known for their capacity to retain dead green and dry needles in canopies over long periods, likely influencing fire severity and behavior.

A Utah partnership has been formed to implement survey, research, education, and management efforts for BWA. Members of concerned stakeholders include the United States Department of Agriculture (USDA) Forest Service; the Utah Division of Forestry, Fir, and State Lands; Utah State University (USU) Extension; USDA Animal and Plant Health Inspection Service; and ski resorts (Fig. 13). This group is coordinating efforts to secure grant funding to study BWA and its impact in Utah and to develop public educational resources.

Fig. 13. *Utah Partnership of Interested Agencies and Stakeholders Attending a Tour of Balsam Woolly Adelgid Damaged Sites in Farmington Canyon, UT.*

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APPENDIX C

UTAH PEST QUARTERLY NEWSLETTER

ENTOMOLOGY NEWS AND INFORMATION

Management and Research Updates on Balsam Woolly Adelgid in Utah

The balsam woolly adelgid (*Adelges piceae*; BWA) is a relatively new forest insect pest to the Intermountain West and Utah. First detected in Utah's Farmington Canyon in 2017, BWA attacks true fir trees including subalpine fir, a highly abundant species across Utah's higher elevations. A decrease in healthy fir forests may lead to decreased watershed health as well as negative impacts on Utah's ecotourism industry.

Monitoring for BWA includes visual inspection on the bole of fir trees for the white woolly masses produced by the insect or other infestation symptoms such as the swelling of branch nodes, called branch gouting. The Forest Service Forest Health Protection (FHP) program has conducted regular monitoring, confirming BWA in Box Elder, Cache, Rich, Weber, Morgan, Davis, Summit, Salt Lake, Wasatch, and Utah counties. Increased range expansion has led to greater interest in monitoring and management activities in both public and private sectors.

Indirect management of BWA in Utah involves thinning and removal of subalpine fir to favor non-host trees such as quaking aspen, lodgepole pine, Douglas-fir, and Engelmann spruce. Regenerating stands and/or planting to replace subalpine fir with non-host species is another approach. Management plans incorporating the promotion of non-host species have been proposed at several ski resorts in northern Utah including Beaver Mountain Ski Area and Snowbasin Resort. Direct approaches to management include single-tree applications of a pyrethroid insecticide or insecticidal soap during critical periods of BWA's life cycle, a practice typically reserved for small-scale management plans such as those used by homeowners.

Research at Utah State University

A USDA Forest Service Research and Development grant is facilitating research on BWA at Utah State University (USU) to better understand its seasonality and dispersal as well as the forest stand characteristics that may increase subalpine fir susceptibility to BWA. These projects aim to provide pest and forest managers with tools and

Branch gouting, or swelling of branch nodes, is a characteristic symptom of an infestation of balsam woolly adelgid on a fir tree. (*Top*)

A subalpine fir bole infested with balsam woolly adelgid; note the white, woolly masses produced by the insect. (*Bottom*)

continued on next page

information to better manage and predict the impacts of BWA in northern Utah subalpine fir forests.

One tool in development at USU is a degree day model for BWA. This type of model uses site-specific temperatures insect phenology to predict the timing for pest management. In the case of BWA, the timing is the crawler stage (youngest nymphs). We regularly collected bark samples and temperature data from five subalpine fir stands throughout northern Utah from August 2020 to January 2023. The results of our data indicate that BWA completes two generations per year in these areas. A degree day model is now being developed to predict the timing of each generation, which can then be used by pest managers to predict when to begin monitoring and implement management actions.

Additional research is being conducted to better understand the interactions between subalpine fir stands and BWA. Over 40 BWA-infested fir stands across northern and central Utah and southern Idaho have been sampled to assess forest structure and composition (species composition, tree size, tree health, etc.). Observation of metrics that specifically describe the impact of BWA on individual fir (crown flagging and dieback, gouting, bole infestations) were also collected. Our results suggest that high levels of die-off due to BWA is not yet frequent in Utah. Characteristics describing stand structure and host stocking levels are likely significant contributors to the observed severity of BWA-related damage. These results suggest that specific treatments (e.g., thinning) which target stands with simple structure and high host composition may be effective in lessening the severity of BWA infestation. Accordingly, a hazard rating system that utilizes these common forest assessment data is being developed to help identify and prioritize stands where BWA is present for treatment.

Another study at USU is investigating dispersal of supposed independent BWA within fir stands across northern Utah. While long-range dispersal mechanisms and patterns are of interest for spread across regions and predicting new infestations, very little is known about the dynamics of BWA within a stand once it is present. Fine-scale dispersal patterns and associated tree (host or non-host) and stand conditions (density) likely influence both the spread of BWA within the stand and its trajectory of population change (increase or decrease).

This study will map BWA-infested subalpine fir stands and measure BWA infestation intensity on each tree as well as other tree and stand characteristics. Individual trees in each stand will be monitored for two growing seasons to detect changes in infestation levels. By using spatially explicit data, tree characteristics can be identified that influence new infestations, support current infestations, and predict future infestations. Fine-scale dispersal patterns and associated tree and stand conditions will inform ecological understanding of how insect pests of sessile plants select hosts and disperse in an environment after initial invasion. This knowledge will also inform future management strategies that target stand structural components and tree-level characteristics to control BWA more effectively in the region.

——— Liz Rideout (M.S. student in Dept. of Biology, USU), Grayson Jordan, and Mike Wayman (M.S. students in Dept. of Natural Resources, USU)

Water Your Pollinators

Pollinators rely heavily on water for their survival. This group of insects—including about 1,000 native bee species in Utah as well as butterflies, moths, wasps, and flies—provide essential ecosystem services for plants, and it is certainly thirsty work. A single bee will visit up to 100 flowers in a single foraging trip and will typically make 10 to 15 trips a day. That's at least 1,000 flowers per day!

Pollen and nectar, however, contain very little moisture, so it is essential for these insects to locate a water source. While worker honey bees will drink water for their own thirst, they will also collect it internally to haul back to the

Nicolefoto/iStockPhoto

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APPENDIX D

CURRICULUM VITAE

Elizabeth Rideout

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Education

M.S. Ecology **Utah State University** 01/2021 – 06/2023
Department of Biology, Logan, UT

M.S. Thesis: “Phenology of the Invasive Balsam Woolly Adelgid (Hemiptera: Adelgidae; *Adelges piceae*) on Subalpine Fir (*Abies lasiocarpa*) in Northern Utah”

Thesis Synopsis: I led field research in Utah on the invasive forest insect, balsam woolly adelgid, to define aspects of its phenology, develop a voltinism degree day model, and provide improved monitoring recommendations for IPM.

Advisors: Dr. Barbara Bentz, U.S. Forest Service Rocky Mountain Research Station; Dr. Diane Alston & Dr. Carol von Dohlen, USU Department of Biology

B.S. Wildlife Ecology & Conservation **University of Utah** 08/2015 – 05/2020
Minor: Geography
Certificate: Applied GIS
Şekercioğlu Laboratory

Work Experience

Agricultural Technician ll **Utah Department of Agriculture & Food**
05/2023 – 11/2023

- Conducted qualitative and quantitative surveying for invasive insects in northern Utah, e.g., emerald ash borer, Japanese beetle, and European spruce bark beetle, regularly maintaining ~100 traps
- Communicated with stakeholders such as homeowners to facilitate trap placement, pesticide applications, etc.

Teaching Assistant **Utah State University, Dept. of Biology**
01/2022 – 05/2022

- Instructed two course sections of introductory biology laboratory (BIOL 1625) to ~45 undergraduate students
- Led course sections in the design, execution, and analysis of weeks-long biological experiment
- Prepared supplementary course materials covering experimental design, data analysis, and ethical research conduct
- Graded exams and lab reports with focus on discovery-based biology and research ethics

Agricultural Technician ll **Utah Department of Agriculture & Food**
05/2020 – 11/2020

- Conducted qualitative and quantitative surveying for invasive insects in northern Utah, e.g., emerald ash borer, Japanese beetle, and velvet long-horned beetle, regularly maintaining ~100 traps
- Produced GIS maps to monitor the spread of Japanese beetle in Utah

Educator/Presenter **Loveland Living Planet Aquarium** 05/2016 – 04/2020

- Developed presentations for and presented to groups of 5-250 about aquatic and terrestrial fauna, conservation, and environmental issues
- Handled 8+ animal species during presentations including reptiles, arthropods, and mammals

Data Collection Assistant **Wild Bee Project** 04/2020 – 10/2020

- Surveyed, collected, and pinned/stored >100 specimens of cabbage aphids and beneficial insects (parasitic wasps, lady beetles, hover flies) from 5 urban organic gardens as part of a population research project

Wildlife Field Intern **Sageland Collaborative** 05/2019 – 09/2019

- Led and assisted with vegetation, topographical, riparian health, and boreal toad surveys in northern and central Utah
- Collected spatial and biological data via pit tagging, banding, and trail camera management
- Operated equipment such as a handheld GPS unit, radio telemetry device, and RTK-GPS for stream, wetland, and vegetation surveys
- Retrieved and managed data in the field and on ArcGIS Pro and Microsoft Excel

Data Collection Assistant **Wild Bee Project** 04/2019 – 10/2019

- Surveyed, collected, and pinned/stored cabbage aphids and beneficial insects (parasitic wasps, lady beetles, hover flies) from 5 urban organic gardens as part of a population research project

Unpaid Experience

Club President **University of Utah Beekeeper's Association**
02/2016 – 05/2020

- Developed and led club meetings and educational presentations
- *Led educational public outreach programs about native and honey bee biology and conservation*
- *Maintained European honey bee hives on the university campus*
- Coordinated roughly 15 students regularly for year-round hive maintenance duties

Research Volunteer **Sekercioğlu Conservation & Biodiversity Lab**
09/2015 – 05/2019

- Used mist nets to capture, band, and record data on songbirds
- Input songbird field data using Microsoft Excel
- Analyzed camera trap datasets in ArcGIS Pro

Research Volunteer **Antelope Island State Park** 04/2017 – 09/2017

- Assisted with banding and biological data retrieval on burrowing owl and American kestrel chicks
- Surveyed and monitored island for wild and artificial owl nests, checking status and marking coordinates

Skills

- Proficient in R programming language and RStudio program
- Excellent oral and written science and public communication
- Effective field, lab, and office team management
- Proficient in Esri's ArcGIS products including map-making and community science application building
- Proficient in Microsoft Suite products
- Comfort in public speaking
- Trained identification of insect, bird, and mammal species
- Able hiker in high elevations and adverse weather conditions

Community Outreach

Utah State University Extension

- Educated Master Gardeners on graduate research and invasive insect ecology and management 2022

USU Entomology Club

- Provided outreach education to adults and children of all ages on insect diversity and conservation 2022

University of Utah Beekeeper's Association

- Interviewed on honey bee biology for documentary film 2020
- Provided outreach education at table displays for conservation events 2018
    - University of Utah
    - Utah's Hogle Zoo
    - Antelope Island State Park
    - Loveland Living Planet Aquarium
- Provided outreach education on honey bees at table display 2017
    - Honeybee Produce Co.
- Developed and led tour presentations about honey bee biology and hives on campus 2017

Loveland Living Planet Aquarium

- Designed and managed full-day event for National Honey Bee Day 2019
- Designed and managed full-day event for Earth Day 2018

University of Utah

- DNA-barcoded wild-foraged mushroom species 2019
- Donated foraged mushrooms to Natural History Museum of Utah 2019
- Built insect collection for donation to university collection 2018

Antelope Island State Park

- Provided outreach education at table display and led nature walks at the annual Spider Fest 2017

Publications

Balsam Woolly Adelgid Fact Sheet 2023

Utah State University Extension

Utah Pests Quarterly Newsletter: Management and Research Updates on Balsam Woolly Adelgid in Utah 2023

Utah State University Extension

Utah Pests Quarterly Newsletter: Research Efforts to Curb Balsam Woolly Adelgid 2021

Utah State University Extension

Presentations - Professional and Outreach

Western Forest Insect Work Conference 2023 (~100 people) 2023

“Seasonal history of the invasive balsam woolly adelgid in northern Utah”

Invasive Tree and Landscape Pest Workshop, USU Extension (~100 people) 2023

“Forest invaders: Balsam Woolly Adelgid & Asian Long-Horned Beetle”

Invasive Pests Workshop, USU Extension (~250 people) 2022

“Emerging invasive forest pest in Utah: Balsam woolly adelgid (BWA)”

Entomological Society of America, Joint Annual Meeting 2022

“Phenology of the invasive balsam woolly adelgid (Hemiptera: Adelgidae, *Adelges piceae*) in northern Utah”

TERRA Society, USU Chapter Meeting (~25 people) 2022

“The balsam woolly adelgid in northern Utah”

First Detector Workshop, USU Extension (~50 people) 2021

“Emerging invasive forest pest in Utah: Balsam woolly adelgid (BWA)”

Western IPM Field Tour (~40 people) 2021

“The balsam woolly adelgid”

Entomological Society of America, Annual Meeting 2021

“Phenology of the invasive *Adelges piceae* (Hemiptera: Adelgidae) in the Intermountain West”

Society of American Foresters, Intermountain Chapter 2021

“Balsam woolly adelgid (*Adelges piceae*) in the Intermountain West”

Entomological Society of America, Pacific Branch Meeting 2021

“Filling life history gaps of the invasive *Adelges piceae* in the Intermountain West”

Kindergarten class visit at Liberty Elementary 2019

“Honey bees!”

Conservation event at Diamond Ridge Elementary (~150 4th grade students) 2019

“The European honey bee”

Professional Affiliations

Entomological Society of America	2021-2023
USU Entomology Club	2021-2023
TERRA Society (USU Chapter)	2021-2022
Utah Beekeeper’s Association	2016-2020
University of Utah Beekeeper’s Association	2016-2020

Awards & Honors

USU Ecology Center Grant	2022
Terry Lee and Faye Marie Whitworth Scholarship	2022
Joseph E. Greaves Endowed Scholarship	2021
USU Ecology Center Grant	2021
Regents Scholarship, Exemplary Academic Achievement Award	2015

Research Interests

- Ecosystem ecology
- Invasive species ecology
- Education/outreach
- Environmental conservation
- Biogeography & GIS

M.S. Supervisor Information

- Dr. Diane Alston, Department Chair of USU Department of Biology (now emeritus)
    - M.S. academic advisor
    - diane.alston@usu.edu
    - Can contact for reference check