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A Severity Rating System for Evaluating Stand-Level Balsam Woolly Adelgid (Hemiptera: Adelgidae) Damage in Two *Abies* Species in Western North America

Kathryn H. Hrinkevich, Robert A. Progar, and David C. Shaw

Severity rating systems are fundamental to understanding the impacts of disturbance agents in forest stands. The balsam woolly adelgid (BWA), *Adelges piceae* (Ratzeburg) (Hemiptera: Adelgidae), is an invasive forest pest in North America that infests and causes mortality in true fir, *Abies* spp. There is currently no single system for evaluating damage caused by BWA in the western United States. Because range expansion through favored habitat is inevitable, it is imperative to begin long-term monitoring using a unified approach to evaluate changing conditions and hasten management opportunities. We developed a new rating system for two western host species: grand fir and subalpine fir. Unlike other severity scales, our index describes stand-level damage rather than impacts on individual host trees alone. We sampled 57 sites across the current range of BWA in the western United States and compiled severity indices using 10 metrics of overstory and understory damage. We used analyses of variance to identify five discrete severity classes and translated the results into a descriptive table of damage characteristics for each class. This index is proposed as an improvement over existing rating systems for western North America because of its broader scope, demonstrated ability to distinguish between classes, and identification of the predominant indicators that will improve the efficiency and efficacy of field assessments. The adoption of this system will facilitate long-term monitoring through site resurveys that will be directly comparable over time, also allowing future studies to conduct risk assessments and target stands that face the greatest threat to forest health.

Keywords: balsam woolly adelgid, invasive insect, nonnative, forest impact, high elevation

Rating systems of forest insect pests are important for understanding the impacts and ecology of these disturbance agents and providing the foundation for monitoring and assessment in integrated pest management programs (Coulson and Witter 1984, Ceisla 2011). The balsam woolly adelgid (BWA), *Adelges piceae* (Ratzeburg) (Homoptera: Adelgidae), is a nonnative invasive forest insect introduced from Europe to North America around 1900. The insect established and spread in northeast North America, infesting and causing mortality of balsam fir (*Abies balsamea*) in New England and Coastal Canada (Balch 1952) and Fraser fir (*Abies fraseri* [Purs] Poir.) in the southern Appalachian region of the United States (Hollingsworth and Hain 1991, Newton and Hain 2005, McManamay et al. 2011). Since then, the adelgid has established infestations in all true firs in eastern and western North America. Currently there are no agreed on rating systems that allow for monitoring and assessment of forest stand impacts for western hosts.

In western North America, the BWA was discovered in California in the 1930s on grand fir (*Abies grandis*), noble fir (*Abies procera*), and European silver fir (*Abies alba*) (Mitchell et al. 1970). During the 1950s and 1960s infestations were observed in Oregon, Washington, and British Columbia on grand fir, pacific silver fir (*Abies amabalis*), and subalpine fir (*Abies lasiocarpa*) (Amman 1962, 1966, Johnson et al. 1963, Mitchell 1966, Wood 1968). Today the insect continues to disperse eastward across Idaho (Ragenovich and Mitchell 2006) and northward into western Montana and British

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; hectares (ha): 1 ha = 2.47 ac.

Columbia (Turnquist and Harris 1993, Livingston et al. 2000, Lass et al. 2014).

The BWA can be very difficult to evaluate because it is a small, inconspicuous, yet complex, insect with a variable life cycle and causes cryptic impacts that vary by geography and host species (Rudinsky 1957, Hain 1988). Unlike that of most fir-infesting adelgids, BWA reproduction is exclusively parthenogenetic, with no known occurrence of males or sexual reproduction (Bryant 1974, Hain 1988), and therefore anholocyclic, having only a single host (Hain et al. 1991). The insect typically has two generations per year; however, the number and timing may vary with altitude and climate (Mitchell et al. 1961, McMullen and Skovsgaard 1972, Bryant 1974, Arthur and Hain 1984, Quirring et al. 2008).

The life cycle of BWA comprises the egg, three nymphal instars, and the adult. The insect overwinters as dormant first instar nymphs (neosistens), referred to as the hiemosistens generation that completes development in the spring (Balch 1952, Greenbank 1970). The first instar nymphs of the second generation (aestivosistens) also undergo a dormant period (summer aestivation) ranging from 2 to 8 weeks (Amman 1969). Adults oviposit 50–200 eggs over a period of weeks and secrete a woolly coating of waxy threads that provides protection for all developmental stages except the crawlers that hatch in early summer. Crawlers are the only motile stage, thus enabling the insect to disperse on birds (Woods and Atkins 1967) and by wind (Lass et al. 2014). On locating a suitable location to settle, the crawlers insert stylets into the living host tissue that inject salivary secretions when the insect is feeding (Johnson and Wright 1957, Greenbank 1970). The late summer generation repeats the cycle of the hiemosistens (Rudinsky 1957, Schooly and Bryant 1978) and completes the life cycle in August or September, becoming dormant neosistens in October (Schooley and Bryant 1978). The reproductive success of BWA fluctuates between generations and is mostly influenced by weather (Greenbank 1970), but the condition of the host tree or vigor and fecundity of the insect may also affect population levels (Schooley and Bryant 1978).

There are several symptoms on branches, stems, and crowns of host trees that indicate the presence and impact of BWA. Prominent swellings around buds and branch nodes, known as gout (Balch 1952), stunt terminal growth and are thought to be caused by the saliva injected into the cortical parenchyma while the insect is feeding (Johnson and Wright 1957, Hain 1988). Abundant branch gout causes the crown to have a sickly or deformed appearance because of the inhibition of new growth combined with the natural shedding of older needles that are not replaced (Overhulser et al. 2004). A more serious type of attack is a mass infestation along the main bole of the tree evidenced by thousands of tiny cotton-like tufts on the tree stem. These stem infestations are variable in their effects on hosts but can cause severe crown damage, branch dieback, and tree mortality within as little as 3 years of establishment (Mitchell 1966).

Crown symptoms in western *Abies* species can range from a low number of branches with gout distortions to severe malformation and dieback throughout the crown. Increasing severity is evident when tree tops become terminally and/or laterally stunted, appearing flattened on top or with an atypical spirelike form (Mitchell 1966, Hain 1988, Ragenovich and Mitchell 2006). Drooping leaders, or top curl, also occurs and may be the result of disrupted water conduction to the top of the tree caused by abnormal cell growth associated with the salivary secretions into host tissue (Doerksen and Mitchell 1965, Ragenovich and Mitchell 2006). In grand fir, the tops of trees with drooping leaders often break off as early as the first winter after the symptom develops (Mitchell 1966). Tree decline caused by branch gout is slow; however, persistent infestations can eventually cause mortality after many decades (Mitchell and Buffam 2001, Overhulser et al. 2004).

BWA severity rating systems being used in western North America are primarily based on the work done by Schooley and Bryant (1978) in Newfoundland in balsam fir forests. Their system and others (e.g., Johnson et al. 1963, Kanoti 2006, Quirring and Ostaff 2008) focus on the assessment of branch distortion and the occurrence of branch dieback to classify overstory trees into severity classes ranging from undamaged to light, moderate, and severe damage categories or categories that differentiate between the extent of branch dieback. Long-term monitoring of BWA infestations in the Pacific Northwest have quantified mortality rates relative to the extent of branch distortion and levels of stem infestation and have made important observations about the patterns of infestation and differences in host susceptibility (Johnson et al. 1963, Mitchell and Buffam 2001). Many studies across North America have used these rating systems to relate environmental characteristics such as elevation, temperature, and soil drainage to BWA-caused tree decline (Brower 1947, Balch 1952, Johnson et al. 1963, Mitchell 1966, Page 1975, Schooley and Bryant 1978, Hain et al. 1991, Livingston et al. 2000, Mitchell and Buffam 2001, Overhulser et al. 2004), but there is little agreement between studies, presumably because of differences between forest ecosystems and the varied responses of host species to infestations.

The existing rating systems focus solely on individual host tree assessments, rather than on stand-level severity metrics, because their emphasis is primarily on tracking host mortality over time and not the overall impact of host decline on stand health or future species composition. This latter measure of impact, which can be directly compared as single-year assessments in diverse forest types, represents an important step toward understanding infestation progression and ecosystem risk.

The ongoing range expansion of BWA in western North America and variability among studies regarding the factors driving damage severity require a reevaluation of the applicability of existing rating systems in western forests. A system tailored specifically to western forest types could reduce uncertainty and provide a consistent monitoring approach. Our goal is to develop a new severity index to quantitatively describe BWA-caused forest decline in the Pacific Northwest at the stand level for grand fir and subalpine fir ecosystems. We propose this system as a means of assessing damage across western fir forests that will facilitate comparisons between ecosystems and over time through the implementation of a unified, single-year "snapshot" rating that can be easily replicated in longer-term monitoring efforts.

Materials and Methods

Data Collection

Site and Overstory Tree Selection

We established 57 study sites across the present range of BWA in the western United States in northern California, Oregon, Washington, Idaho, and western Montana in an attempt to select sites across the geographical range of BWA (Figure 1). These sites included homogeneous stands of grand fir or subalpine fir or mixed stands containing both host and some nonhost species, all with

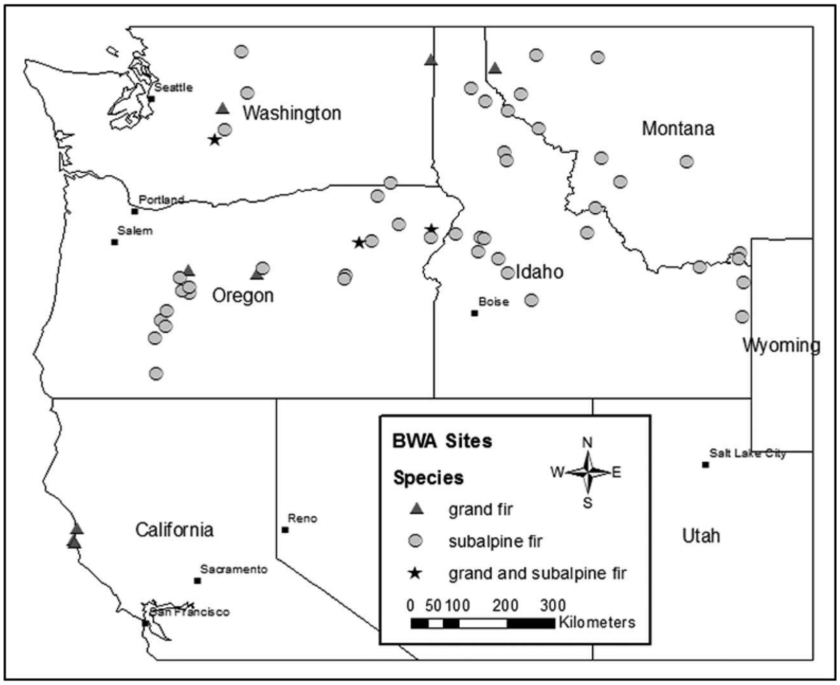

Figure 1. Study site distribution map with reference to species sampled.

known BWA infestations. We recorded sampling date, latitude and longitude, elevation, slope, and aspect at the plot center and used this location to select up to 12 trees of each host species by taking a compass azimuth every 30° and choosing the live overstory host tree closest to the bearing and within 60 m of center. Each tree was labeled with an aluminum numbered tag for which species, height, and dbh were recorded. Any additional disturbance agents (insects or pathogens) or external damage to trees in the site were noted; however, sites were selected to minimize confounding disturbances wherever possible to avoid conflicting damage assessments. In sites with evidence of other defoliators, we attempted to isolate and evaluate BWA-related symptoms only. Stem infestations were noted when present, but they were not included in the rating systems because of their ephemeral and unpredictable occurrence.

Overstory Tree Symptoms and Stand Structure

The crown of each tagged tree was divided into vertical thirds and BWA-related percent branch dieback (Figure 2) was estimated in each third using six classes: 0 = 0%, 1 = 1–24%, 2 = 25–49%, 3 = 50–74%, 4 = 75–99%, and 5 = 100% dead branches. The maximum total rating for a live tree was 14. The most severe degree of gout (node or branch swelling) (Figure 3) observed for the entire tree was recorded in four classes based on observations of the range of gout severity on each host species: 0 = no gout, 1 = light branch distortion, 2 = moderate branch distortion, and 3 = severe branch distortion. Because of the subjectivity involved in rating gout related to anatomical differences between species and tree size or age, our ratings reflect an assessment of the distinctness of observable swelling relative to a healthy branch on each tree (Table 1). We recorded the presence and type of all crown deformities (Figure 4) associated with adelgid damage. Three crown deformities were possible, including top curl where the apex of the tree curls to one side or another, stunted terminal in which the apical stem elongation has been deformed into a flattened top appearance, and stunted lateral branches that are not elongating and create a spirelike crown. We summed all observed deformities for a maximum of three per tree. This variable was an additional surrogate metric for the extent and severity of gout in the upper crown, which frequently could not be determined because of limited visibility of branch nodes in tall hosts, even with the use of binoculars. Although the extent and severity of crown damage and foliage loss in the upper crown have been used in other studies (e.g., Johnson et al. 1963), we believe the addition of a crown deformity metric that can be consistently and reliably assessed is necessary to adequately represent upper crown damage. It also eliminates problems associated with differences between western host species, some of which are damaged from the top down and those that sustain damage from the bottom up (Mitchell 1966), by

Figure 2. Photo of damage type dieback.

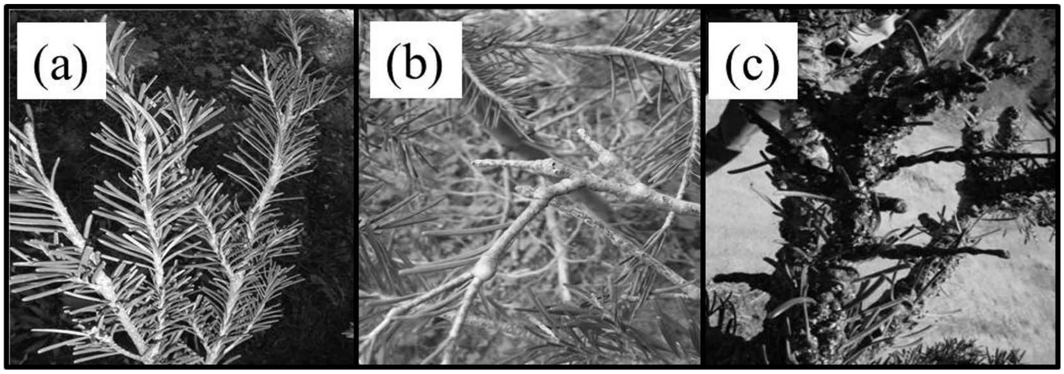

Figure 3. Photo of damage type gout: light (a), moderate (b), and severe (c).

Table 1. Variables used to develop the severity rating.

Variable	Rating	Rating description 0	1	2	3	4	5
Dieback (%)*	0–5	0	1–24	25–49	50–74	75–99	100
Crown deformity†	0–3	None	One deformity observed	Two deformities observed	Three deformities observed		
Gout	0–3	Undetectable	Light swelling, indistinct without close examination	Moderate swelling, distinct on bare and foliated branch tips	Severe swelling, distinct, prominent branch distortion		
Percent mortality (host impact)	0–1	Overstory basal area (m^2/ha) or understory density (stems/ha) dead host/total host basal area or density					
Percent mortality (stand impact)	0–1	Overstory basal area (m^2/ha) or subcanoopy density (stems/ha) dead host/total basal area or density for all species					

Each variable was rated for overstory trees (>12.7 cm dbh) and understory trees (10 cm height–12.6 cm dbh) for a total of 10 variables. Each value was normalized from the original scale to values between 0 and 1 for equal weighting and then summed to produce the final rating.
* Dieback estimates for overstory thirds were averaged into a single value representing the entire crown (0–4.67 scale) but were noted as single estimates for all understory trees (0–4 scale). Although only live hosts were evaluated for dieback, the assessment scale included a category for 100% dieback to account for sections of the canopy thirds that were entirely dead.
† Individual crown deformities were noted, including top curl, stunted terminal branches, and stunted lateral branches. The total number of observed deformities was used in the analysis.

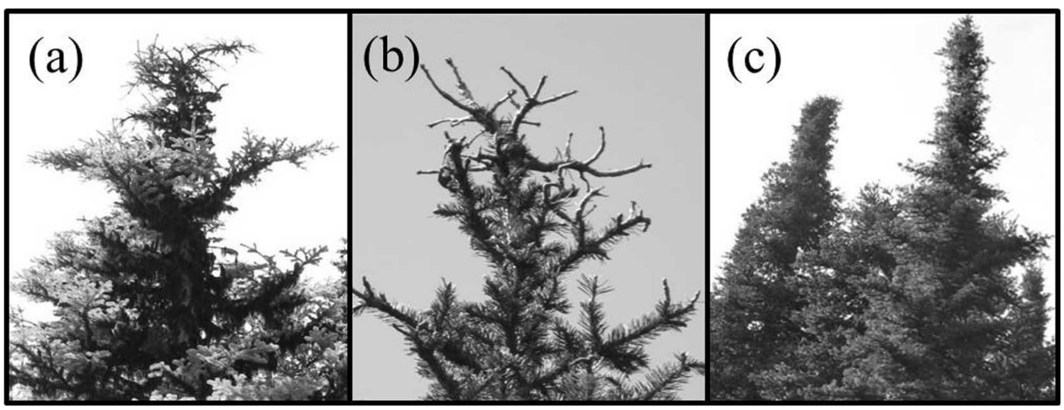

Figure 4. Photo of damage type crown deformity: top curl (a), stunted terminal branches (b), and stunted lateral branches (c).

ensuring that difficult-to-see top-down damage is represented in the assessment.

To assess overstory composition and mortality, we selected the four tagged trees closest to the 90°, 180°, 270°, and 360° azimuths from plot center as locations to record live and dead overstory basal area for all species in the site. We estimated basal areas using a 20 basal area factor wedge prism that we converted to a metric basal area factor of 4.59 to calculate values in m^2/ha.

Understory Symptoms and Stem Structure

Four variable radius circular plots were established at the same four locations where we conducted overstory basal area sampling. We used these plots to calculate the density and composition of the understory (live and dead stems) and evaluate BWA symptoms on live host species. Understory plot radii ranged between 1.6 and 8.0 m, depending on understory density, to ensure a minimum of ≈10 stems per plot. We counted live and dead understory trees below the 12.7-cm dbh overstory limit by species in each plot. Each live understory host was evaluated for BWA symptoms using the same damage classifications described for overstory trees (percent branch dieback, gout severity, and number and type of crown deformities). We estimated percent branch dieback of understory trees for the entire crown rather than in crown thirds because all branches were easily visible.

Data Analysis

Index Development

The three stem-specific metrics (percent dieback, gouting severity, and number of crown deformities) were averaged for each site by host species. We averaged the sum of the crown third values for overstory branch dieback first to obtain a single dieback estimate for each tree on a scale of 1 to 4.67, with 4.67 representing the maximum crown damage value for a living tree with an original crown third sum maximum value of 14. Gout severity and the total number of crown deformities in the overstory trees were averaged for each host by site on scales of 0 to 3. For the understory, we averaged percent dieback on a scale of 0 to 4 and gout severity and total number of crown deformities on scales of 0 to 3. Basal area (overstory) and stem density (understory) were converted to m^2/ha and stems/ha, respectively, and the totals for all species (live and dead) from the four sampling locations were averaged for each site.

We used the above ratings of BWA symptoms to derive five overstory and five understory variables to produce an index of stand-level BWA damage. These 10 variables were chosen because they are the best indicators of BWA-related decline (e.g., Balch 1952, Mitchell 1966, Schooley and Bryant 1978, Mitchell and Buffam 2001, Ragenovich and Mitchell 2006). Our index includes site averages for the following overstory and understory variables: (1) percent branch dieback class, (2) gout severity class, (3) number of crown deformities, (4) proportion of total hosts killed by BWA, calculated as (total dead host)/(total live and dead host), hereafter referred to as host impact, and (5) proportion of host mortality relative to all species present, calculated as (total dead host)/(total live and dead host and nonhost), hereafter referred to as stand impact (Table 1).

All final index variables were normalized to a scale between 0 and 1 because the original measurement scales were different (dieback 0 to 4.67 [overstory] or 0 to 4 [understory]; gout and number of crown deformities, both 0 to 3), which would have disproportionately biased the importance of variables measured on larger scales. We normalized using the equation

$$\frac{a + (X - A) \cdot (b - a)}{B - A}$$

where a and b represent the desired scale limits ($a = 0$, $b = 1$) and A and B represent the lowest and highest possible values of the original scales (reported above), with X representing the value being normalized. For a scale of 0 to 1 this equation simplifies to X/B. The mortality variables (host and stand impact) were already represented by percentages between 0 and 1, such that higher numbers indicated higher impacts of mortality on the host or the stand. The resulting equally weighted 10 normalized variables (5 overstory and 5 understory) were summed by site into a total severity index value for each host species.

Statistical Analysis

Subalpine fir and grand fir were analyzed separately because of different responses documented between the two hosts to BWA infestations in different habitats (Mitchell 1966). Variables were log transformed where necessary to meet the assumptions of the statistical procedures used. We conducted three separate analyses. First, we tested for overall differences between grand fir and subalpine fir severity index values across all sites using an independent samples Welch's t-test assuming unequal variances. We chose Welch's test because sample size differences between subalpine fir ($n = 49$) and grand fir ($n = 11$) would be unlikely to meet the equal variance assumption.

Second, we categorized the sites into distinct severity classes designated by 1-point intervals in the severity index values (0–0.99 as class 1, 1–1.99 as class 2, etc.). We tested for differences between severity classes with 10 one-way analyses of variance (ANOVAs) for each of the 10 variables in the index, using a Benjamini-Hochberg correction on the P values to control the false discovery rate associated with conducting multiple tests (Benjamini and Hochberg 1995). Significance was determined based on an α value of 0.05. We used Tukey's honestly significant difference post hoc tests to determine where differences occurred between severity classes for each variable in the index (Table 2). If groups did not meet the equality of variance assumption, we used Welch's ANOVA to determine significance.

Last, we calculated Spearman rank correlations between each variable in the index and the total severity index value to examine which factors most influenced severity. We used this analysis to support our interpretation of the ANOVAs and to assess the contribution of each variable to the total rating.

Results

Overall Differences between Grand Fir and Subalpine Fir Severity Indexes

The results of Welch's t-test comparing severity indices showed that index values were significantly higher for subalpine fir ($n = 49$, mean $= 2.85$, SD $= 1.00$) than for grand fir [$n = 11$, mean $= 1.40$, SD $= 0.60$), $t(47) = 13.69$, $P < 0.001$]. The total number of sites tested ($n = 60$) reflects that 3 of our 57 sites had both subalpine and grand fir dominant trees.

Differences in BWA Symptoms between Severity Classes

We identified five levels of increasing BWA-related decline when we partitioned the index values into 1-point interval severity classes (Table 2). Grand fir sites were distributed across classes 1 and 2 (index values 0–1.99), and subalpine fir fell into classes 2 through 5 (index values 1–4.99). The distributions of sites across severity classes were between 3 and 16 sites per class (Figure 5).

Descriptive statistics for each of the BWA symptoms tested (Table 2) were used to define the characteristics of each class. For example, average dieback near 1 corresponds to an average 1–24% branch dieback, near 2 corresponds to a 25–49% rating, and so on. The results of the ANOVAs for each symptom (Table 2) show where variables significantly differed between classes and were used to determine whether 1-point intervals along the index were appropriate to represent distinct classes and increasing degrees of severity.

Severity Class Differentiation

Severity class 1 for grand fir was characterized by 25–50% dieback, sparse incidences of crown deformities (less than one symptom per stem), little to no gout, and no mortality in the overstory. The understory of class 1 sites was generally unaffected, with little to no dieback, sparse incidences of crown deformity (less than one symptom per stem), little to no gout, and no mortality. In class 2 we observed significant increases in overstory damage for gout severity (to ratings of light to moderate), Welch's $F(1, 6) = 23.78$, $P_{\text{corrected}} = 0.0026$, and significant increases in understory damage for incidences of crown deformities (to more than half of stems showing one symptom) and gout severity (to ratings of light), all $F(1, 8) = >6.95$, all $P_{\text{corrected}} = <0.017$. Mortality was rarely observed in grand fir at these two lowest class levels (Table 2).

Table 2. Means (SDs) of coded variables (coding explained in text) with ANOVA results testing differences between severity class groups for each variable.

	Severity class				
Variable	1	2	3	4	5
Grand fir					
n	3	7	0	0	0
Overstory					
Dieback	1.21 (0.23)	1.42 (0.43)			
Crown deformity	0.47 (0.47)	0.54 (0.45)			
Gout	0.03 (0.05)[a]	1.18 (0.62)[b]			
Mortality (host)	0.00 (0.00)	0.01 (0.01)			
Mortality (stand)	0.00 (0.00)	0.01 (0.01)			
Understory					
Dieback	0.10 (0.11)	1.01 (0.64)			
Crown deformity	0.09 (0.09)[a]	0.57 (0.17)[b]			
Gout	0.10 (0.11)[a]	0.78 (0.28)[b]			
Mortality (host)	0.00 (0.00)	0.06 (0.06)			
Mortality (stand)	0.00 (0.00)	0.03 (0.03)			
Subalpine fir					
n		11	16	15	6
Overstory					
Dieback		1.41 (0.46)[a]	1.73 (0.50)[ab]	2.01 (0.58)[b]	2.14 (0.53)[b]
Crown deformity		0.77 (0.30)[a]	0.95 (0.36)[ab]	1.25 (0.43)[ab]	1.14 (0.34)[b]
Gout		1.03 (0.29)	0.99 (0.42)	1.27 (0.51)	1.30 (0.51)
Mortality (host)		0.04 (0.08)[a]	0.34 (0.29)[b]	0.52 (0.25)[b]	0.58 (0.025)[b]
Mortality (stand)		0.01 (0.03)[a]	0.13 (0.12)[b]	0.33 (0.16)[c]	0.45 (0.022)[c]
Understory					
Dieback		0.84 (0.37)[a]	0.94 (0.37)[ab]	1.32 (0.49)[bc]	1.82 (0.45)[c]
Crown deformity		0.51 (0.19)[a]	0.63 (0.26)[ab]	0.81 (0.20)[bc]	0.91 (0.05)[c]
Gout		0.77 (0.34)[a]	0.92 (0.36)[ab]	1.36 (0.59)[bc]	1.88 (0.55)[c]
Mortality (host)		0.05 (0.04)[a]	0.10 (0.11)[a]	0.10 (0.09)[a]	0.48 (0.28)[a]
Mortality (stand)		0.03 (0.03)[a]	0.07 (0.08)[a]	0.09 (0.08)[a]	0.35 (0.24)[b]

Superscript letters a, b, and c indicate significant differences between severity groups for a given variable. *P* values were corrected for multiple comparisons using the Benjamini-Hochberg method to control the false discovery rate based on an $\alpha = 0.05$.

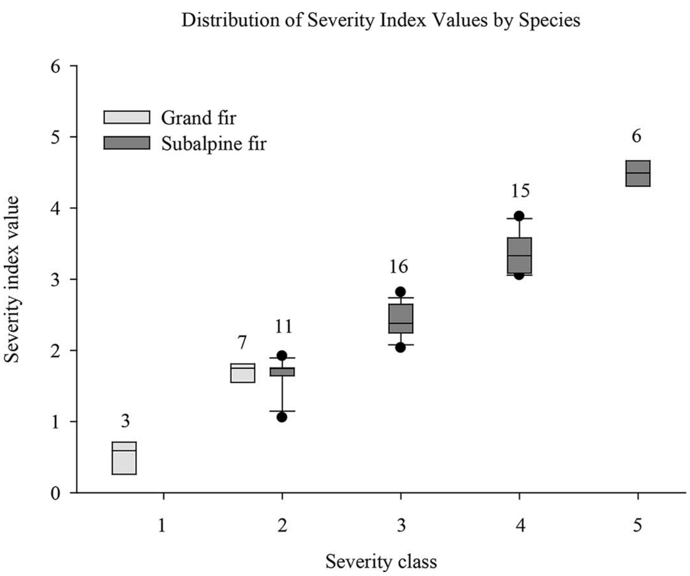

Figure 5. Distribution of severity index values by classes and species. Boxplots show 10th and 90th percentiles (whiskers), 25th and 75th percentiles (boxes), median values (line), and outliers (points). The number of sites included in each class is noted above each plot.

For subalpine fir, significant severity class differentiation occurred in all BWA symptoms except overstory gout severity, which maintained light to moderate levels across all classes. No sites fell into the lowest severity class because dieback, gout, and crown deformities were more prevalent in both the overstory and understory of subalpine fir stands than those observed for grand fir, resulting in cumulative index values exceeding 0.99 at all sites. Severity class 2 was characterized by 25–50% branch dieback, low incidences of crown deformity (single symptom per stem), light to moderate gout severity, and little to no mortality in the overstory (0–10% host impact; 0–5% stand impact). The understory was similar in all characteristics with a slightly lower incidence of branch dieback (near 25%) and fewer incidences of crown deformity (less than one symptom per stem). Severity class 3 was distinguished by significant increases in overstory mortality to ratings of 25–50% host impact, Welch's $F(3, 17) = 28.36$, $P_{corrected} = 0.001$, and 0–25% stand impact, Welch's $F(3, 15)=33.32$, $P_{corrected} = 0.0005$ (Table 2). Class 3 understory severity was the same as that for class 2.

The only variable distinguishing class 4 from class 3 was a significant increase in overstory stand impact mortality (to ratings of 25–50%), Welch's $F(3, 15) = 33.32$, $P_{corrected} = 0.0005$. Class 4 was significantly differentiated from class 2 by an increase in branch dieback (to consistently greater than 25% with a mean closer to 50%) and greater incidences of crown deformity (to ratings of 1–2 per stem) for both overstory and understory trees, significantly greater overstory host impact mortality (greater than 50%), and significantly greater understory gout severity ratings (closer to moderate), all $F(3, 44) = >3.78$, all $P_{corrected} = 0.0189$. Severity class 5 was similar in most characteristics to class 4, distinguished by significant increases in understory mortality to well above 25% (up to 75% host and 50% stand impact), all Welch's $F(3, 16) = >5.60$, all

$P_{corrected}$ = 0.011 (Table 2). All three lower severity classes had understory mortality levels (host and stand impact) well below 25%. We summarized the differences between classes from the ANOVAs into text descriptions (Table 4) and then generalized the defining characteristics (Table 5).

Spearman Rank Correlations

Spearman rank correlations between the component variables and the total index values (Table 3) for grand fir indicate that the extent of branch dieback is the only significant overstory variable significantly correlated with stand-level severity. All symptoms in the understory are significantly related to the final severity index value, with the extent of branch dieback showing the strongest correlation. For subalpine fir, correlations between the component variables and total severity are nearly all significant, with the exception of the extent of gout in the overstory trees, consistent with the ANOVA results. Overstory mortality and the incidence of understory crown deformities were the strongest indicators of stand-level severity for this species.

Discussion

A New Severity Rating System

We developed a rating system to evaluate BWA impacts for grand fir and subalpine fir in the Pacific Northwest. Our rating included evaluations of branch dieback, incidences of crown deformity, gout severity, and host mortality. The variables were combined into an index that describes stand-level impact, integrating host and nonhost information from both overstory and understory tree species. We have shown that the severity rating system can be used to classify stand-level BWA damage into statistically distinct classes for the two *Abies* species most susceptible to BWA infestation in the western United States. The severity index values and classes represent a distinct phase of stand decline that can be quantified, which, when used as a routine part of forest health assessments provides a much needed tool for land managers to monitor the progression and spread of BWA infestations. Specifically developed in and for western fir forests, this system may also work well in this region for additional *Abies* species that are less susceptible to infestation.

We did not include a stem infestation metric in our index because, although indicative of a current active population in the stand, it is a transient condition and not a direct symptom of damage. We encourage the inclusion of information about stem infestations in forest health surveys to ensure that all BWA activity is reported and treated as a contributing factor to what may be a complex of disturbance agents. Because BWA infestations restricted to the crown can persist as long as 70 years before causing mortality, resurgence of residual adelgid populations in stem attacks even decades after the original infestation established can hasten damage (Johnson and Wright 1957, Mitchell and Buffam 2001) and should be monitored to help guide management decisions.

Table 3. Nonparametric Spearman rank correlations between severity indices and the component variables of each index.

	Grand fir		Subalpine fir	
	Canopy	Subcanopy	Canopy	Subcanopy
Dieback	0.70*	0.86*	0.46*	0.58*
Crown deformity	−0.05	0.66*	0.50*	0.60*
Gout	0.36	0.81*	0.22	0.58*
Basal area/density mortality (host)	0.47	0.66*	0.73*	0.44*
Basal area/density mortality (stand)	0.47	0.67*	0.82*	0.46*

* Significant correlations ($\alpha = 0.05$).

Comparison with Other Rating Systems

Existing rating systems focus primarily on individual overstory host species and do not account for the impact of BWA-caused host tree decline on overall stand health. We developed a system to address the need for a stand-level rating system that can be used to

Table 4. Properties of defined site severity classes for grand fir and subalpine fir derived from ANOVA results and descriptive statistics of index variables.

	Property
Grand fir	
1	*Overstory*: Dieback 25–50%, sparse incidences of crown deformity (less than one symptom per stem), little to no gout, no mortality.
	Understory: Generally unaffected. Little to no dieback, sparse incidences of crown deformity (less than one symptom per stem), little to no gout, no mortality.
2	*Overstory*: Dieback 25–50%, sparse incidences of crown deformity (less than one symptom per stem), **significant increase in gout (light to moderate),** 0–1% mortality for host and stand.
	Understory: Dieback 0–25%, **significant increase in incidences of crown deformity (less than one symptom per stem), significant increase in gout (light), 0–10% mortality for host,** 0–5% mortality for stand.
Subalpine fir	
2	*Overstory*: Dieback 25–50%, light incidences of crown deformity (single symptom per stem), light to moderate gout, 0–10% mortality for host, 0–5% mortality for stand.
	Understory: Dieback 0–25%, sparse incidences of crown deformity (less than one symptom per stem), light to moderate gout, 0–10% mortality for host, 0–5% mortality for stand.
3	*Overstory*: Dieback 25–50%, light incidences of crown deformity (single symptom per stem), light to moderate gout, **significant increase in mortality (25–50% for host, 0–25% for stand)**.
	Understory: Dieback 25–50%, sparse incidences of crown deformity (less than one symptom per stem), light to moderate gout, 0–10% mortality for host, 0–5% mortality for stand.
4	*Overstory*: Dieback 50%, light incidences of crown deformity (one to two symptoms per stem), light to moderate gout, 25–50% mortality for host, **significant increase in mortality for stand (25–50%)**.
	Understory: Dieback 50%, moderate incidences of crown deformity (one to two symptoms per stem), moderate to severe gout, 0–10% mortality for host and stand.
5	*Overstory*: Dieback to 50–75%, moderate incidences of crown deformity (one to two symptoms per stem), moderate to severe gout, 25–75% mortality for host and stand.
	Understory: Dieback 50–75%, moderate incidences of crown deformity (one to two symptoms per stem), moderate to severe gout, **significant increase in mortality (25–75% for host, 25–50% for stand)**.

Characteristics in bold indicate symptoms that significantly differentiate that severity class from the class below it, as defined by ANOVA.

Table 5. Generalized descriptions of the ratings for the five-class BWA severity system, accounting for stand-level overstory and understory conditions.

Rating	Overstory and understory characteristics
1	Minimal damage, BWA detectable
Dieback	0–20%
Crown deformities	0–1
Gout	Light to undetectable
Host mortality	0–1%
Stand mortality	0–1%
2	Noticeable damage
Dieback	2–40%
Crown deformities	1
Gout	Light
Host mortality	2–10%
Stand mortality	2–5%
3	Moderately damaged stand, understory decline very visible
Dieback	41–60%
Crown deformities	1–2
Gout	Moderate on bare and foliated branch tips
Host mortality	11–30%
Stand mortality	6–25%
4	Severe damage and very noticeable decline in overstory and understory
Dieback	61–80%
Crown deformities	2–3
Gout	Severe and distinct gout on most branches
Host mortality	31–50%
Stand mortality	26–40%
5	Severe damage, *Abies* species near extirpation from the stand
Dieback	81–100%
Crown deformities	3
Gout	Severe, but can be moderate, often found throughout entire crown
Host mortality	51–90%
Stand mortality	41–90%

assess current damage and future species composition by incorporating mortality indicators and understory assessments into a severity index that also includes the typical overstory indicators symptomatic of BWA-caused damage. We included an additional crown deformity metric intended to improve branch deformity assessments in the upper crown of tall trees characteristic of western fir forest types. Our BWA severity rating is of broad scope and quantitatively distinguishes between severity classes in two western host species. The adoption of this system will facilitate direct comparisons between surveys to examine the role of environmental (e.g., elevation, soil drainage, latitude, and climate) and stand-level (e.g., age, forest structure, and species composition) drivers of severity that will ultimately aid in predicting range expansion and ecosystem risk.

Evaluation of Grand and Subalpine Fir Damage Classes, Proof of Concept

The results of the ANOVA to determine whether 1-point intervals along the index were appropriate to represent five distinct classes with increasing degrees of damage severity validated the concept that successive classes showed significantly greater damage in one or more of the symptoms measured (Table 4). The increase in severity from class 1 to 2 for grand fir was defined by light damage beginning in the understory. With no observed increase in understory mortality or change in overstory damage, this demonstrates the greater resistance of grand fir over that of other host species in the mountainous west (Mitchell and Buffam 2001) and its capacity to withstand long periods of infestation without significant damage to the overstory. This supports the observations of Mitchell (1966) that, over time, adelgids begin to drop into the understory and begin branch infestation of understory trees.

The overstory and understory characteristics of subalpine fir were similar to those of grand fir in the lowest severity class observed for this species (class 2), with slightly higher overstory dieback and crown deformity. Increases in overstory mortality distinguished the next higher class (class 3), followed by further increases in stand-level mortality in class 4 and more pronounced understory decline where dieback, incidences of crown deformity, and gout severity increased, but only significantly when compared with those in class 2. The most severely affected subalpine fir stands were defined by pronounced increases in understory mortality where host losses are altering the current and future stand composition and structure. At these levels, it is likely that the true fir component of the stands as the dominant species will be lost. Even subalpine fir in the understory of some mixed species stands was severely declining with up to 50% understory mortality, but the pure subalpine fir stands that have already incurred as much as 75% understory mortality are not likely to recover to previous conditions.

The lack of importance of the gout severity as an indicator of BWA decline in the overstory of both species demonstrates the utility of including a crown deformity metric in our severity index. These species grow to heights that make direct gout assessments difficult, particularly in older, closed stands where lower branches have been shaded out or dropped. Crown deformities provide a proxy measure with which to assess branch distortion caused by the increasing extent of gout in the upper branches where nodes are less visible. In the understory where the incidence of gout remains easily detectible, significant increases did differentiate between increasing severity classes; therefore, it remains an important variable to include in the index, demonstrated by the high correlations with total severity.

Application to Regional Field Use

The BWA stand rating system presented here will be a benefit to forest health professionals working in the West as previous systems do not integrate tree and stand characteristics in the evaluation of damage caused by BWA. Because BWA has been present in some areas for decades and is currently spreading in the Rocky Mountains, it is imperative to begin long-term monitoring using one system throughout the West. As an example of the utility of the system, we compared grand fir and subalpine fir.

As possible field applications, we back-transformed the quantitative ratings into generalized classes (Table 5) and included photos of typical damage symptoms (Figures 2–4). We present this tool as a potentially more efficient rating system that does not require extensive field sampling and data analysis. This concept requires further testing to determine whether field personnel could accurately rate a stand using qualitative estimates from Table 5 that were consistent with the quantitative measures they were derived from. At present, the field readiness of a generalized assessment tool is unknown; however, the adoption of the quantitative approach is a necessary first step to begin comparative studies. We recommend using our plot layout because of its successful application across the diverse stand structures found in western fir forests, but any layout that systematically quantifies the overstory and understory conditions included in the rating could be used. Detecting subtle differences in stand health and linking them to stand or environmental attributes would probably benefit from a higher concentration of sampling sites rather than fewer, large sampling plots that could potentially average out subtle indicators. For this study, plot boundaries defined by 12 randomly selected overstory trees efficiently and effectively met our objective to stratify stand-level damage across a range of severity classes. This layout should provide a useful framework for instituting our procedure in new ecosystems.

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