Fundy Model Forest Final Report 2008

Development of Hazard Ratings for the Balsam Woolly Adelgid

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Executive summary

The balsam woolly adelgid (hereafter BWA) was introduced into Canada from Europe early in the century, occurs on both coasts, and has caused extensive tree damage to balsam fir in Atlantic Canada. Its lack of wings results in limited dispersal and infestations build up locally, causing an irregular or spotty distribution of outbreaks. Affected trees are unsuitable for lumber owing to uneven shrinkage causing warping and splitting, and pulp is of inferior quality to that from normal wood. Stem attack can result in growth reductions in excess of 50%, with high populations killing large trees within three years. Chronic crown infestation can cause a tree to succumb in 10 to 20 years and also predisposes trees to infection by a root-rot. Unfortunately, there is no commercially viable tactic to deal with this pest. During two years of field surveys, branch distortion or 'gout' caused by BWA feeding was evident throughout southern and eastern New Brunswick and throughout most of Nova Scotia and Newfoundland. We did not observe any BWA feeding on the main stem of balsam fir trees. Trees visibly damaged by BWA occurred in areas where mean January temperatures were > -11C and in plant hardiness zones > 4a. The mean annual percentage of stems with gout was positively correlated to mean annual January temperatures, indicating that variations in damage are highly correlated to overwintering temperatures. Over 75% of the variation in the incidence of gouting by BWA during the past 10 years in the 7 plant hardiness zones in New Brunswick was explained by mean January temperature, site, shoot growth (estimated by the square of shoot length), and whether the trees were in the overstory or understory. Understory trees contained much higher levels of gout than overstory trees. The

incidence of gouting was parabolically related to shoot length, suggesting that BWA will not damage the most vigorously growing shoots and trees. Although damage by BWA was often slightly higher in precommercially thinned stands during the first 10 years following thinning, damage levels in thinned and adjacent unthinned stands were similar $\geq$ 15 years after thinning. Damage may have increased slightly during the first few years following thinning due to the concentration of BWA on fewer stems per unit area and to slower growth rates resulting from thinning shock. This may have been followed by reductions in damage 5-10 years after thinning when trees in thinned stands would have had higher growth rates. Testing this hypothesis would require annual estimates of growth rates and gouting and should be carried out in future studies. Growth rates in thinned and unthinned stands were probably similar 15 years after thinning, when damage by BWA was similar in both stand types. The distribution of BWA should increase westward and northward if winter temperatures increase. To minimize damage by BWA, balsam fir should be grown in areas with the coldest overwintering temperatures (eg., at higher altitudes and on north-facing slopes) and in areas where tree growth rates are high.

Objectives

a) To determine the frequency and intensity of damage by balsam woolly adelgid populations in managed and unmanaged balsam fir stands.
b) To determine whether BWA damage is associated with other stand characteristics

Background

The balsam woolly adelgid (BWA) was introduced into Canada from Europe early in the century, occurs on both coasts, and has caused extensive tree damage. BWA has a high biotic potential because of its high fecundity and parthenogenetic method of reproduction. Its lack of wings results in limited dispersal and infestations build up locally, causing an irregular or spotty distribution of outbreaks (Balch 1952). Affected trees are unsuitable for lumber owing to uneven shrinkage causing warping and splitting, and pulp is of inferior quality to that from normal wood. Stem attack can result in growth reductions in excess of 50%, with high populations killing trees of merchantable size within three years. Chronic crown infestation can cause a tree to succumb in 10 to 20 years (Carroll and Bryant 1960). Damage also predisposes trees to infection by *Armillaria* root-rot (Hudak and Singh 1970).

There has been only limited success in reducing damage caused by BWA using insect predators or chemicals (Harris and Bowers 1995). The resurgence of BWA in New Brunswick in the past few years in balsam fir, the principal component of wood supply, is of particular concern. Similar concerns occur in Nova Scotia, Newfoundland (Milne 1990) and Maine. Earlier studies indicated that thinned stands, in which many trees developed deep crowns, may have suffered more damage than neighbouring, fully-stocked stands (Balch 1952). With the anticipated future wood shortages and the increased costs of intensive forest management, it is important to determine the occurrence and significance of the insect in high-value stands and evaluate the role of the BWA in managed stands.

During the past two summers, we surveyed BWA damage in thinned and unthinned fir stands in New Brunswick. Within a subset of these stands we measured stem density, development stage of stand, elevation, aspect, percentage slope, soil moisture, soil type, soil texture, depth of humus layer, ground vegetation and tree growth rate. We also used data collected by the New Brunswick Department of Natural Resources (Hartling 2004, Lavigne 2005) to relate the presence and absence of BWA to stand characteristics and temperature. Finally, we also measured the incidence of gouting during the previous ten years in New Brunswick and carried out analyses to determine whether the level of damage was related to winter temperatures.

Although only two authors are listed on this report, data in it are the result of our collaboration with colleagues from the Departments of Natural Resources of New Brunswick (Nelson Carter, Lester Hartling and Dan Lavigne), Nova Scotia (Keith Moore and Mike LeBlanc), and Newfoundland and Labrador (Hubert Crummey), as well as the Canadian Forest Service (Ian DeMerchant).

Methods

Influence of site factors and thinning on BWA Damage

In each stand, 5 plots located at 30 m intervals were established to determine the type (stem attack vs. branch distortion or 'gout') and intensity of damage caused by BWA in thinned and unthinned balsam fir stands of varying ages in southern New

Brunswick. In addition, the following data was collected from each stand: number of stems (by species), pre-spacing density, development stage of stand (regenerating (1-2m), sapling (<7m and < 10 cm DBH), young (10 < x < 16 cm DBH), immature (16 < x < 26 cm DBH), mature/overmature (> 26 cm DBH), bearing of cruise, elevation, aspect, percentage slope, soil moisture regime (dry, fresh, moist, or wet), soil type (podzol, brunisol, gleysol, organic, etc.), soil texture, depth of humus layer, and ground vegetation (major species). Five trees closest to the centre of each plot were rated for gout using a rating scheme developed by Schooley and Bryant (1978). To facilitate the exchange of information with provincial entomologists, crown or gout attack was classified using the same five categories used by DNR.

In addition, we were provided with BWA damage estimates from a DNR survey of several hundred plots throughout New Brunswick. Although no other stand characteristics were directly measured in this survey, we were able to obtain many stand characteristics from the New Brunswick GIS database.

Influence of temperature on BWA damage

Preliminary analyses that related mean temperatures from November, December, January and February, obtained from weather stations located throughout New Brunswick, suggested that the distribution of damage by BWA was best explained by January mean temperatures. Consequently, mean monthly temperature rasters were generated using 1971- 2000 long-term mean monthly temperature layers provided by the CFS-Great Lakes Forestry Centre (http://cfs.nrcan.gc.ca/subsite/glfc-climate) for January for all regions of Newfoundland, New Brunswick and Nova Scotia. When these temperature values were compared to a sample of measured normals from weather stations, they were generally within 0.5°C of one another, suggesting that they provide accurate estimates of winter temperatures. The distribution of plots with and without evidence of BWA damage was plotted and contours were generated at -11°C and -10°C.

The distribution of plots with and without BWA damage was also overlaid on Canada's plant hardiness zones (McKenney *et al*. 2001; McKenney *et al*. 2007) available at (http://planthardiness.gc.ca/ph_main.pl?lang=en). These plant hardiness zones were based on earlier work by Ouellet and Sherk (1967a,b,c) and take into account various site conditions, such as minimum temperature of the coldest month, mean frost free period, amount of precipitation, monthly mean of the warmest month, mean maximum snow depth and maximum wind gust speed.

In 2006 in a subset of the stands described above, one midcrown branch from two trees per plot (i.e., 10 trees per stand) was cut with pole pruners and the incidence of gouting by BWA on the terminal axis was recorded. As midcrown branches had up to 10 age-classes of foliage, this enabled us to estimate the incidence of gouting for the previous 10 years. The incidence of branch gouting during the 10-year period was related to January temperatures.

Influence of temperature, tree growth rate and tree size (understory or overstory) on damage

To evaluate the relative influence of plant growth rate and temperature during the last 10 years on annual variations in percent gouting, we selected 2 stands close to a weather station in each of 7 plant hardiness zones (i.e., zones 2b, 3a, 3b, 4a, 4b, 5a and 5b). To estimate the amount of damage caused by BWA, five plots, located 30-m apart, were established along a linear transect within each stand. One east-facing branch in the upper and one east-facing branch in the lower crown in each of the two overstory trees closest to the plot centre were removed using pole-pruners. The incidence of gouting on shoots on one half of the branch (including the main axis) was observed and recorded for all shoots up to 10 years old. Mean proportion gouting per year was calculated for the branch and values from the two branches were combined to produce a mean gouting estimate per tree. As gouting may influence shoot growth, shoot growth was estimated by measuring the lengths of shoots without gout on two additional trees per plot. Two east-facing branches (one in the upper and one in the lower crown) were selected in the same way as the branches selected for gouting. Shoot lengths along the main branch axis were measured to estimate shoot length. In all plots in all 14 stands, two under-story trees were sampled for gout and two additional trees were sampled to estimate shoot length using the same procedures as for over-story trees.

Analyses

General linear models were used to evaluate the relative influence of the measured stand variables, expressed on a stand level to avoid pseudo-replication, on the level of damage attributable to BWA in thinned and adjacent unthinned stands. General linear models were also used to evaluate the influence of the many site factors on damage by BWA, and to determine the effect of tree size (over-story versus under-story), annual temperature and annual growth rate (shoot length) on the proportion of shoots with gout. Proportion data was arcsin transformed. Regression analysis was used to evaluate the influence of mean winter temperatures or of shoot length on the incidence of gouting by BWA. The square of shoot length explained a greater proportion of the variation in BWA damage than shoot length and therefore was used in all analyses.

Influence of site factors and thinning on BWA Damage

BWA damage was usually highest in stands where the water table was higher or lower than normal, suggesting that trees may have been more stressed and grew at a slower rate. Consequently, these results suggest that increases in tree growth rate, resulting from thinning, should not make trees more susceptible to BWA. Our analysis supports this hypothesis. There was no general and consistent increase in BWA damage that could be attributed to thinning, although damage was slightly higher in thinned stands (Fig 1). Levels of BWA damage were also influenced by elevation, crown closure, volume and height of trees of dominant tree species, density of dominant tree species, and basal area of dominant tree species. These trends were often curvilinear and were not consistent enough to be considered for a hazard rating.

Influence of temperature on BWA damage

In New Brunswick, damage by BWA was only observed in the southern and eastern (near the coast) region of the province (Fig. 2). This distribution appears to be strongly influenced by winter temperatures. The presence or absence of damage by BWA was more closely related to mean January temperatures than to mean temperatures for the months of December, February or March. All balsam fir stands containing trees damaged by BWA occurred in areas where the mean annual temperature in January was above -11°C (Fig.2). Many of the stands examined in regions where the mean January temperatures were between -10 and -11°C did not contain trees damaged by BWA, whereas most stands in warmer regions contained BWA-damaged trees. Thus the -11°C mean January isotherm can explain the presence or absence of BWA damage in all stands surveyed in New Brunswick. All areas of Nova Scotia and all areas of Newfoundland that were surveyed had mean January temperatures above -11°C, and most stands surveyed in both provinces showed evidence of BWA damage.

The presence/absence of BWA in New Brunswick was also strongly related to plant hardiness zones. Damage by BWA was absent in all regions with a plant hardiness rating of 4a or lower, but was present in all regions with a plant hardiness rating of 4b or higher (Fig. 3). A couple of BWA damaged stands in western Newfoundland appear to occur in plant hardiness region 4a (Fig. 3), but this may be a result of the highly variable terrain, with respect to elevation, sun exposure and wind exposure, in the area.

Temperature also explained year-to-year fluctuations in the level of damage by BWA. The incidence of gouting along the central axis of mid-crown branches was positively related to mean temperature during the preceding January (Fig. 4).

Influence of temperature, tree growth rate and tree size (understory or overstory) on damage

Mean January temperature, shoot length (squared), tree size (overstory or understory) and site all explained a significant proportion of the annual variation during the past 10 years in the incidence of gouting in the 7 plant hardiness zones throughout New Brunswick ($p < 0.001$). Together, they explained over 75% of the annual variation in gouting ($F_{13,213} = 58.716$, $p < 0.001$). When temperatures were expressed using 2.5C categories, mean

January temperature explained over 90% of the variation in gouting (Fig. 5). As found previously for gall-forming adelgids, the proportion of shoots with gout was parabolically related to shoot length (Fig. 6), an estimate of tree growth rate.

Gouting in the under-story was positively related to the proportion of shoots with gout in the over-story ($y = 0.457x + 0.034$, $r^2 = 0.\ 0.44$), although levels of gouting were consistently higher in the under-story. Higher levels of gouting in the understory may be associated with warmer winter temperatures, due to snow cover.

Discussion

It is clear from this study that temperature plays an important role in determining the presence or absence of BWA. Generally, BWA does not occur where mean January temperatures are < -11C. The presence/absence of BWA can also be predicted using plant hardiness zones, as BWA does not occur in zones colder than Zone 4a. Just as the presence/absence of BWA in an area can be predicted based on temperature, so can the severity of attack in regions where BWA is present. The incidence of gouting was positively related to the mean temperature in January, supporting the findings of Greenbank (1970), who reported a similar phenomenon for survival of overwintering nymphs.

Several stand variables explained variations in BWA damage when examined alone. However, when large multivariate analyses were carried out these variables were often not significant. This is probably due to reduced sample sizes for extreme values of these variables as well as the non-linear (usually curvilinear) relationships often observed between stand characteristics and BWA damage. Our study suggests that inconsistent conclusions concerning the influence of various site factors on BWA damage may result from their different effects on tree growth rates, and the non-linear relationship between tree growth rate and BWA damage.

Precommercial thinning has reportedly increased levels of defoliation of balsam fir by an indigenous insect, the balsam fir sawfly, *Neodiprion abietis* (Moreau et al. 2006). Similarly, opening up stands that have just experienced crown closure, as occurs in precommercial thinning, results in increased defoliation by the spruce bud moth, *Zeiraphera canadensis*, an indigenous defoliator on white spruce (Osaff and Quiring 2000). The good news for the forest industry and woodlot owners is that there is not a large effect of precommercial thinning on the level of BWA damage. We have found a similar trend in Newfoundland (data not shown), lending support to this conclusion.

Slightly increased levels of BWA damage following thinning may have resulted from the concentration of BWA onto a reduced number of trees or to slower tree growth rates resulting from post-thinning shock. Trees in thinned stands should have had higher growth rates than trees in adjacent unthinned stands from 5-10 years after thinning, when differences in BWA damage decreased. Trees in thinned and unthinned stands probably had similar growth rates 15 years after thinning, when BWA damage levels were similar.

The parabolic relationship between shoot length and the incidence of gouting is similar to that reported for galling adelgids (McKinnon et al. 1999) and other gallers (Quiring et al. 2007). Gall adelgids induce a gall by secreting a chemical into the primary phloem (Sopow et al. 2003). Successful gall induction appears to depend on the dose of the gall-induction stimulus (Sopow et al. 2003) and a bigger dose of induction stimulus is required to induce a gall on a large shoot (Flaherty and Quiring 2008). Thus galling adelgids are usually unable to survive and produce galls on fast-growing trees. This study indicates that balsam woolly adelgid may interact with its host in a similar manner. Although BWA does not produce a gall within which juveniles can feed, it does cause the host tree to produce a novel structure, referred to as gout.

In contrast to previous studies that were not able to explain a large proportion of the variation in BWA damage with measured variables, we were able to explain approximately 75% of the variation in the incidence of gouting by BWA throughout the 7 plant hardiness zones of New Brunswick during the past 10 years with four variables: mean January temperature; shoot length squared; site and tree size (overstory or understory). Shoot length squared or mean January temperature, by themselves, were able to explain the majority of the variation in gouting. This suggests that woodlot owners and the forest industry can minimize damage by BWA by limiting, as much as possible, stands with high balsam fir content to cold micro-climatic regions (eg., on the north sides of slopes or at high altitude) and to high-quality (with respect to growth) sites.

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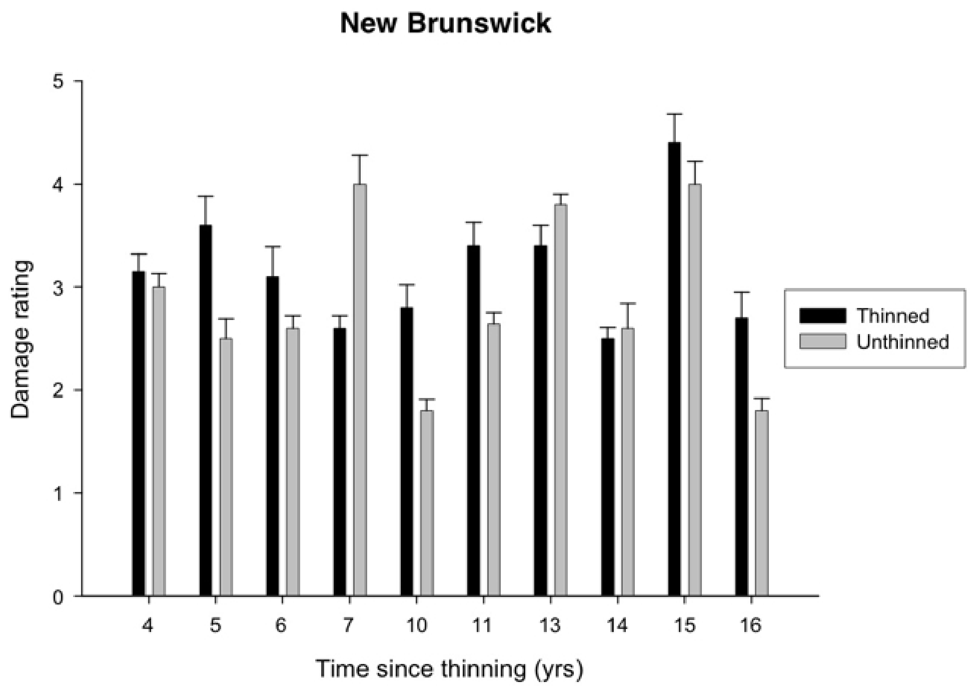

Fig. 1. Mean (± SE) damage by BWA in fir stands in southern New Brunswick thinned during the last 16 years. Damage ratings vary from 0 (no visible damage) to 5 (upper crown or entire tree was killed by BWA).

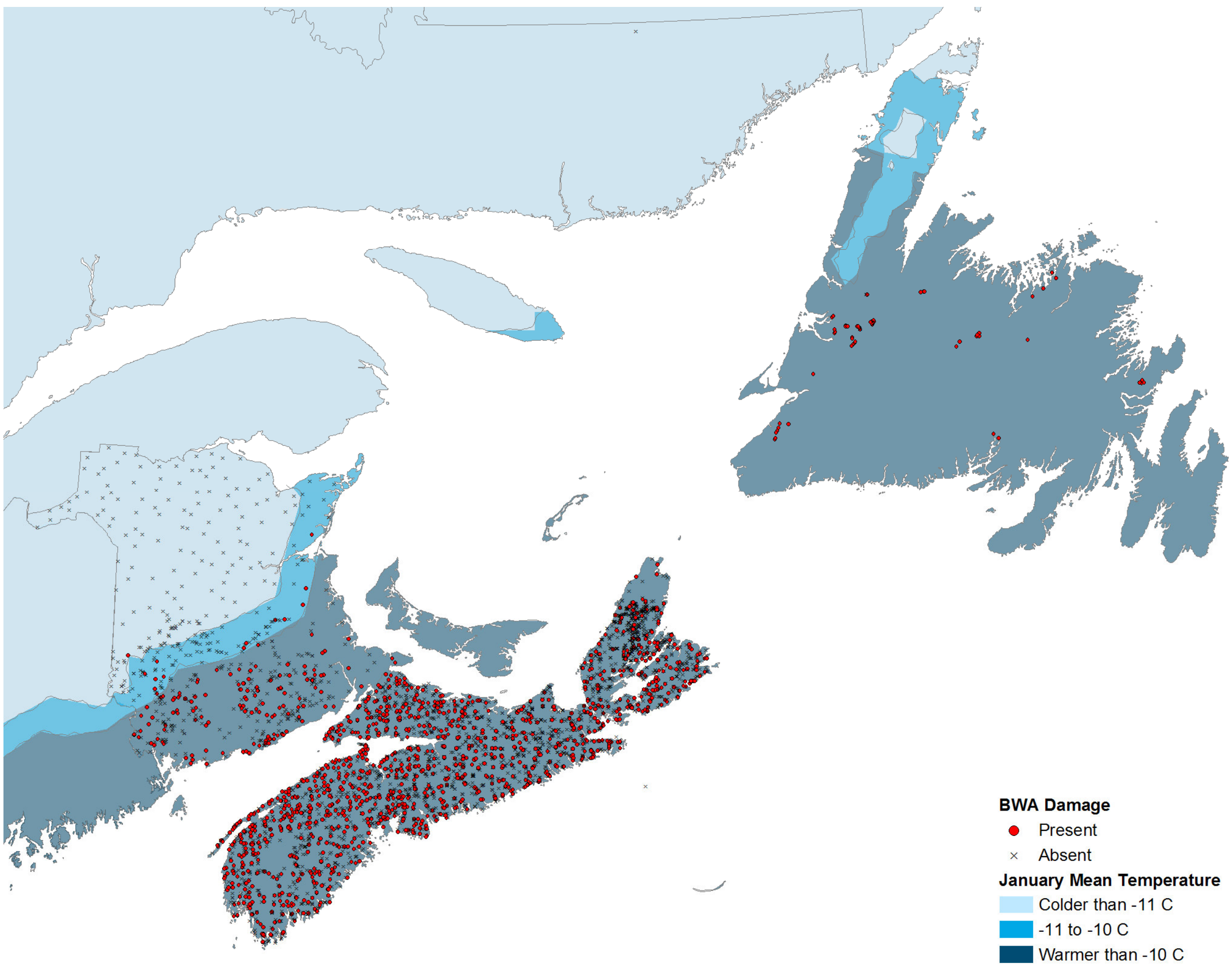

Fig. 2. Relationship between areas in New Brunswick, Newfoundland and Nova Scotia with mean annual temperatures <-11°C, -10 to -11°C, and >-10°C during January and presence (circles) or absence (x's) of damage attributable to BWA.

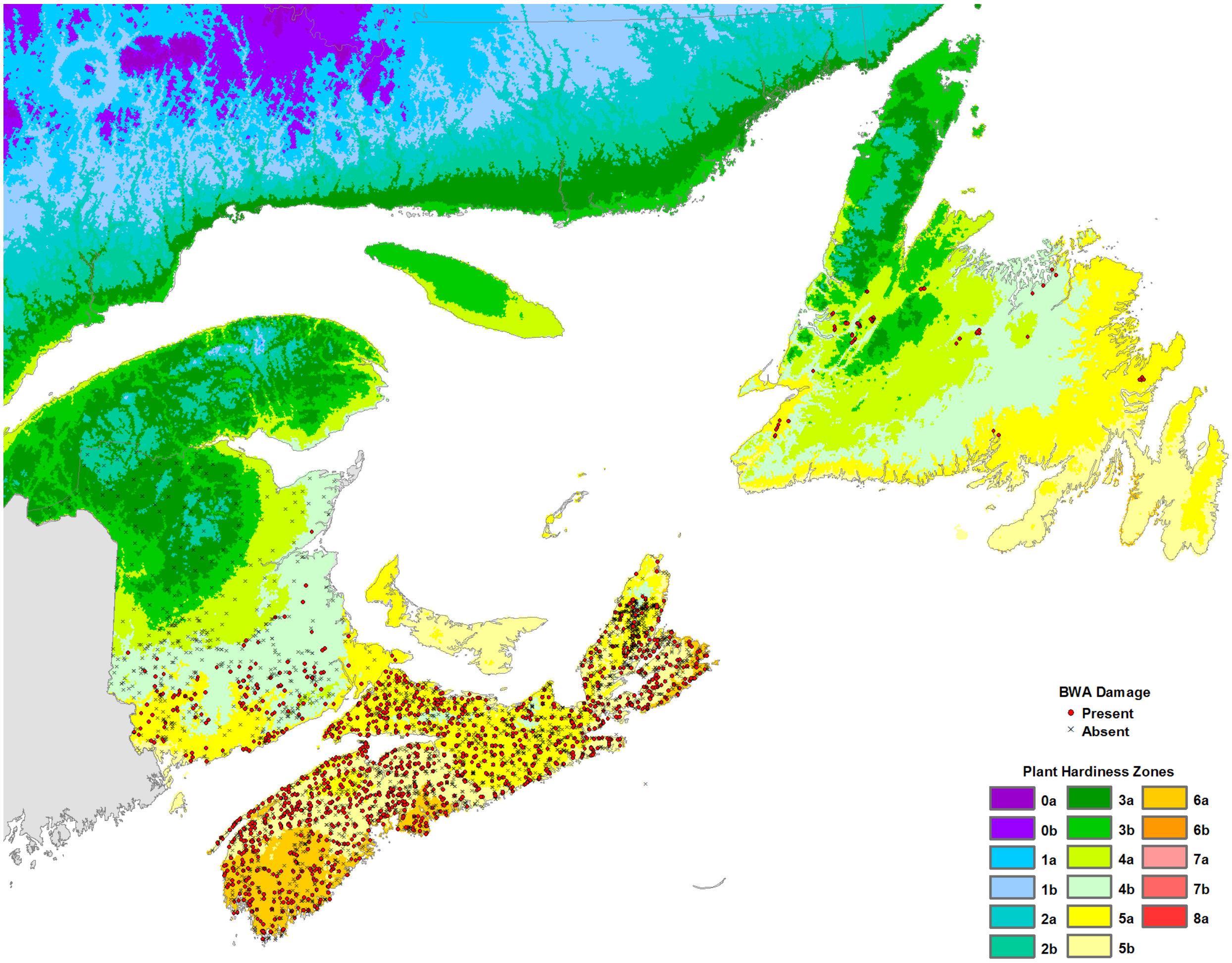

Fig. 3 Relationship between plant hardiness zone and presence (circles) or absence (x's) of damage by BWA in New Brunswick, Newfoundland and Nova Scotia.

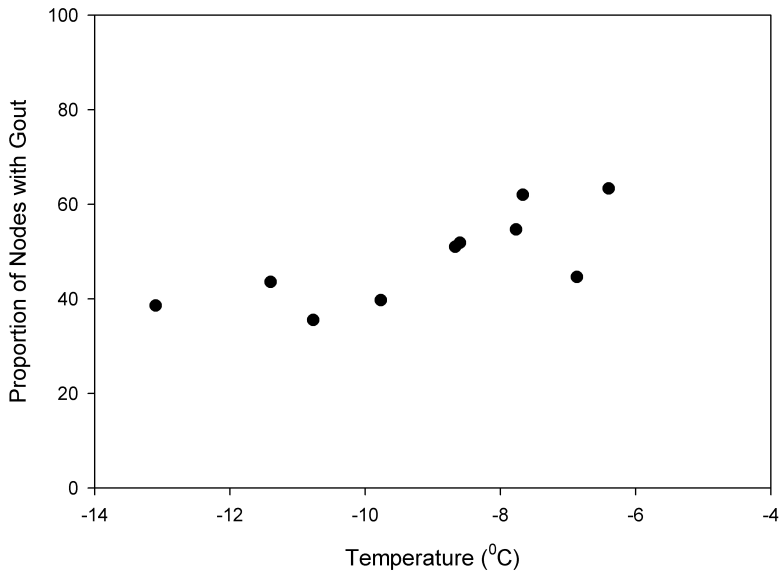

Fig. 4. Relationships between the mean January temperature from 1995-2005 in New Brunswick and the mean proportion of terminal shoots that developed the following summer that showed evidence of gouting caused by BWA. $R^2 = 0.67$, $p = 0.004$.

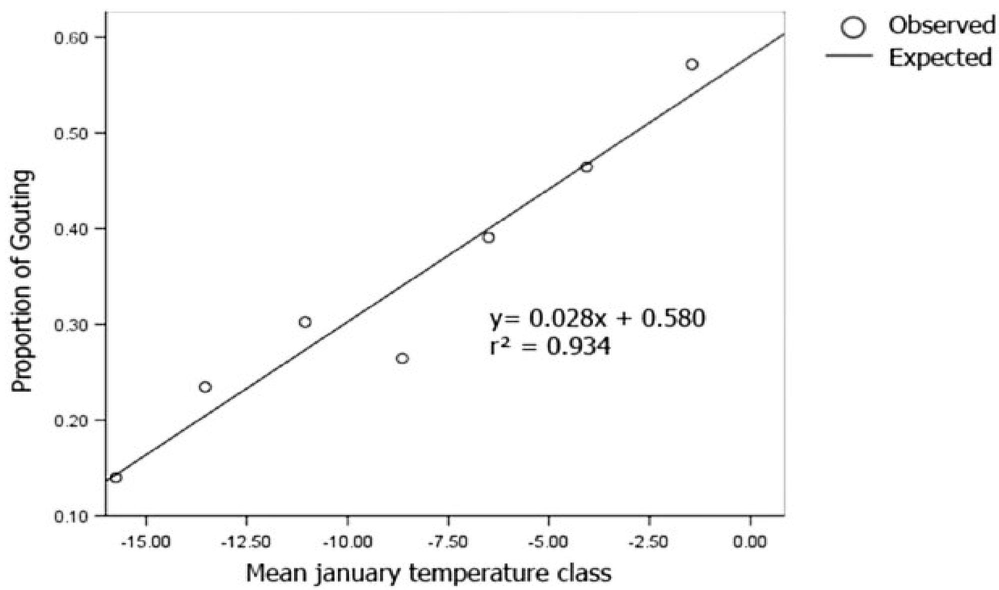

Fig. 5. Relationship between mean January temperature (expressed in 2.5C categories) and mean proportion of shoots with gout for under-story and over-story balsam fir trees.

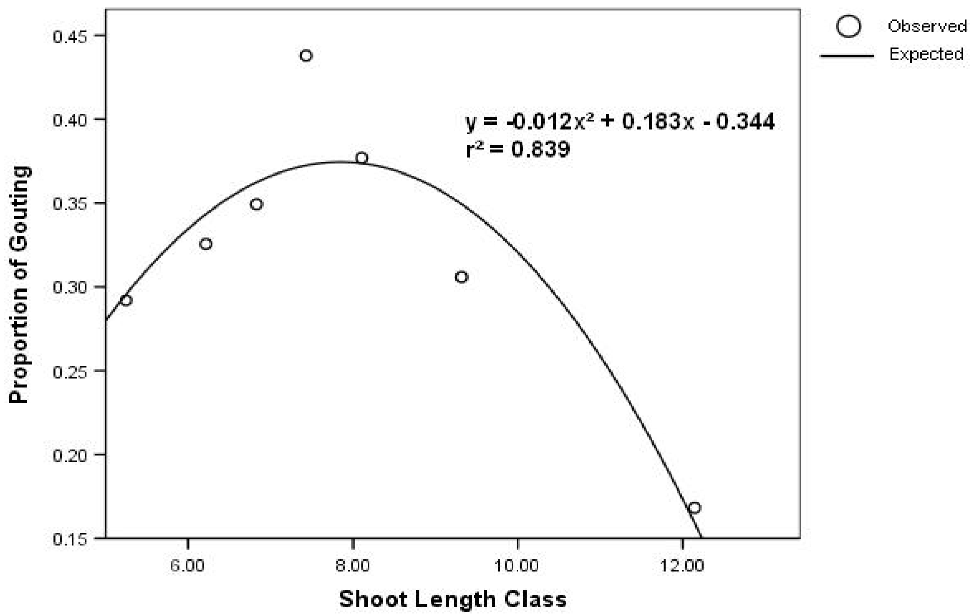

Fig. 6. Relationship between mean proportion of shoots of balsam fir (over-story and under-story) with gout by BWA and mean shoot length (cm).