Canadian Journal of Forest Research
Revue canadienne de recherche forestière

The Effect of Leader Damage on White Spruce (*Picea glauca*) Site Tree Height Growth and Site Index

Journal:	<i>Canadian Journal of Forest Research</i>
Manuscript ID	cjfr-2017-0056.R1
Manuscript Type:	Article
Date Submitted by the Author:	05-May-2017
Complete List of Authors:	Nigh, Gordon; British Columbia Ministry of Forests and Range
Keyword:	British Columbia, frost damage, insect damage, modelling, site tree selection
Is the invited manuscript for consideration in a Special Issue? :	N/A

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2 **Height Growth and Site Index**

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Abstract

Site trees used to estimate site index are selected based on characteristics that ensure that the tree reflects the potential productivity of the site. Hidden leader damage can make it difficult to identify site trees. Using these trees as site trees could lead to erroneous estimates of site index and height growth trajectories. One hundred and fifteen white spruce (*Picea glauca* (Moench) Voss) trees were selected, harvested, and split open to identify hidden damage and to quantify the effect of the damage on height growth and site index. A mixed-effects height growth model based on the Chapman-Richards function was formulated. A height growth modifier was included in the model to estimate the effect of leader damage on height growth. It was found that height growth was reduced by 28% in the year that the damage occurred, and by 6% and 3% in the following two years. This results in a reduction of about 0.16 m in site index per incidence of damage on average, although this will depend on the age when the damage occurred and the timing between damage events. Since the damage is not outwardly visible, this creates problems when developing and applying site index models.

Key words: British Columbia, frost damage, insect damage, modelling, site tree selection

Introduction

Site index is the height of a site tree at a reference age and is a measure of site productivity, i.e., the potential to produce wood (Skovsgaard and Vanclay 2008). Site index has two main purposes: as a productivity indicator to consider when prescribing some silviculture treatments such as fertilization (Province of British Columbia 1985), and to calibrate site index models¹. Site index (or height-age) models project the height of a site tree to a specified age. Site index models are important tools for forest management because of the linkage between height and stand volume (e.g., Eichhorn 1902, Gehrhardt 1921, as reported by Skovsgaard and Vanclay 2008). This linkage is often exploited in growth and yield models to predict stand volume with height as a predictor variable (e.g. Mitchell 1975). Growth and yield models are used in forecasting timber supply and consequently setting allowable annual harvest levels.

In British Columbia (BC), Canada, site index is defined as the height of a site tree at the reference age of 50 years at breast height. A site tree has the following characteristics by definition (B.C. Ministry of Forests and Range 2009):

- the largest diameter tree at breast height of the target species in a 0.01 ha sample plot
- dominant or co-dominant
- free of suppression above breast height
- not a wolf, open-grown, or veteran tree
- straight-stemmed, free of disease, decay, insect damage, and other significant damage including forks, scars, and breakage

¹ Base-age invariant site index models obviate the need to calibrate the models with site index since they can be calibrated with any height-age data point. However, the issues addressed in this research are relevant to any calibration point.

- vigorous with a full crown.

This definition is similar to other jurisdictions (e.g. United States Department of Agriculture Forest Service 2015). Site trees should exhibit unimpeded height growth (Carmean 1975, Green *et al.* 1989, Krumland and Eng 2005, Monserud 1984, Monserud 1985) so that the growth reflects the potential productivity of the site rather than the effects of non-site factors.

The Site Index – Biogeoclimatic Ecosystem Classification (SIBEC) model can be used to estimate site index in BC when site trees are not available on a site (Mah and Nigh 2003). This model predicts the site index for a given species and site series (an ecosystem with uniform environmental conditions) as classified according to the Biogeoclimatic Ecosystem Classification (BEC) system (Meidinger and Pojar 1991). Data acquisition for the SIBEC model requires establishing temporary sample plots on a site of the target site series containing site trees of the target species, then averaging the estimated site index from the height and breast height age of the site trees from the sample plots. A downward trend is apparent when the white spruce (*Picea glauca* (Moench) Voss) SIBEC site index data are plotted against the age of the sample tree (Fig. 1). This trend has been noticed for some, but not all, species in the SIBEC data warehouse. The trend line in Fig. 1 was fitted using segmented regression with the unknown break point being estimated by nonlinear regression (Sen and Srivastava 1990). The average site index for white spruce drops from 24.55 m for sample trees at breast height age 10 to 18.45 m for sample trees at age 50. Downwards trends in site index in other, smaller, data sets have also been noticed. The cause of this trend requires further investigation. Many studies have found long-term trends (mostly increases) in forest productivity with climate change (e.g., Kirilenko and Sedjo 2007), making climate change a potential candidate to explain the trend in Fig. 1. This trend may also indicate that the height growth of site trees is being influenced by non-site factors

that are correlated with age, which would confound the interpretation of site index and could result in biased growth and yield predictions.

This trend is unlikely to be a model-based issue since it is seen across different species and for different models that are used to estimate site index. For example, the site index estimates in Fig. 1 are obtained from the site index model published in Thrower *et al.* (1994). However, a similar trend exists if the site index estimates are obtained from other site index models for white spruce. Time trends in site tree dominance (Magnussen and Penner 1996) could cause this trend but was tested and found to only cause a minimal reduction in site index over time (Nigh 2016).

Another possible source for this trend in site index is leader damage. Harding (1986) noted that terminal leader failure could alter height growth and that “reductions in height for dominant trees would affect determinations of site quality using height as the index” (Harding 1986). Leader damage that is serious enough to reduce height growth could cause a gradual decrease in estimated site index as a tree ages if the tree experiences more damage events over time. It could also contribute to trends in site tree dominance discussed above.

Since the mid 1990’s, stem splitting has replaced traditional stem sectioning for reconstructing the height growth of some species in BC such as white spruce. This reveals a surprisingly large amount of leader damage that was concealed by radial stem growth in white spruce trees that had been selected as site trees (i.e., undamaged) based on a visual ground inspection (Nigh and Love 1999). These trees do not meet the definition of a site tree and should not be used to estimate site index. A site index estimate made from a tree with height growth that is affected by leader damage is not a good measure of site productivity because this estimate of

site index measures not only site productivity but also the effects of leader damage on height growth.

The purpose of this study was to determine whether leader damage could result in the decreasing trend in estimated white spruce site index with age. Three objectives were established to meet this goal: i) determine the amount of leader damage, ii) develop a model to quantify the effects of leader damage on height growth, and iii) since the true site index is not known for trees with damage, use the model to estimate and evaluate the effects of leader damage on site index.

Data

The data for this project come from stem analysis of immature white spruce trees in the moist cold subzones of the Interior Cedar–Hemlock (ICH) and Sub-Boreal Spruce (SBS) biogeoclimatic zones and the dry cool subzone of the SBS zone (Meidinger and Pojar 1991). These subzones are located in northwestern BC near the town of Smithers (54°46'55"N 127°10'05"W). The ICH zone is transitional between the coast and interior of BC hence it is warm and moist in the summer and cold in the winter (Banner *et al.* 1993). The SBS zone is continental with warm and moist summers and severe, snowy winters (Banner *et al.* 1993).

Potential sampling areas were identified from silviculture records. Stands that had a history of harvesting or fire such that the trees would now be 10 to 40 years old at breast height were visited. A potential white spruce sample tree was identified within these stands. If the tree met the requirements for a site tree (see Introduction for a definition of a site tree), then a 0.01 ha circular plot was established at that location. An increment core was taken to ensure that the tree was free from suppression. A careful external examination of the stem for damage, insect attack, and disease was made from the ground. One hundred and fifteen site trees were sampled within the budget.

The sample trees were felled and delimbed. The stem was then examined for external signs of damage that were missed during the ground inspection of the standing tree due to heavy foliage obscuring the damage or the damage being too high to discern from the ground. The height above breast height where the damage occurred was noted so that the corresponding point where annual height growth stopped and a terminal bud was set (the node) could be found after splitting the tree.

The sample trees were split by creating crosscuts at short regular intervals along the stem that go through the pith but not all the way through the stem and using splitting wedges to open up the stem. Branch whorls were used to identify nodes when the stem was too small to split. The heights of the nodes above breast height were recorded along with notes about any damage at the node. All of the stem damage that was noted was forking. Forking is indicated by a crook in the pith where a lateral branch took over as the leader after the leader was aborted. The node number above breast height corresponds to the breast height age of the tree. Breast height age will henceforth be referred to as age for brevity because all ages are taken from breast height. The ages of the sample trees ranged from 10 years to 42 years except for one tree that was 60 years old. The sampling resulted in a series of height – age data from breast height age 1 up to the age of the tree. Since height growth was the response variable of interest, the height data were converted into growth data by taking the difference of annual heights. Age was adjusted by half a year so that age is the midpoint of the growth interval. For example, height growth from age 1 to 2 was obtained by subtracting the height at age 1 from the height at age 2 and age was adjusted to be 1.5.

Methods

Histograms showing the number of incidents of leader damage by breast height age, by 1 m height classes, and by years before sampling were produced. Summary statistics on the number of incidences of damage were produced for all damage and for damage that was visible from an external examination after the trees were felled.

A modelling approach was taken to assess the impact of leader damage on the height growth of site trees. A Chapman-Richards function (Richards 1959) was chosen as the base function for the site index model (eq. 1):

$$(1) \quad H = 1.3 + a_0 \times (1 - e^{-a_1 \times A})^{a_2}$$

where H is height (m), A is breast height age (yrs), e is the base for natural logarithms, and a_0 , a_1 , and a_2 are unknown parameters to be estimated. A height growth model was created by differentiating eq. 1 with respect to age. The growth model was formulated as a mixed effects model to account for tree-to-tree variation in height growth rates, and a multiplicative modifier was included in the model to account for leader damage, resulting in the following height growth model (eq. 2):

$$(2) \quad Hg_{ij} = D_{ij} \times (a_0 + b_{0i}) \times (a_1 + b_{1i}) \times (a_2 + b_{2i}) \times e^{-(a_1 + b_{1i}) \times A_{ij}} \times (1 - e^{-(a_1 + b_{1i}) \times A_{ij}})^{(a_2 + b_{2i}) - 1} + \varepsilon_{ij}$$

where the subscripts index tree (i) and observation within tree (j), Hg_{ij} is annual height growth rate (m/yr), b_{0i} , b_{1i} , and b_{2i} are random effects, D_{ij} modifies the height growth to account for the effects of leader damage, ε_{ij} is the random error term with the usual regression assumptions (Sen and Srivastava 1990), and all other variables and parameters are as defined for eq. 1. The random effects are assumed to be multivariate normally distributed with a mean of 0 and with unstructured variances and covariances that are estimated from the data.

The modifier D_{ij} is the means to understanding the effects of leader damage on height growth. It represents a proportional reduction (or, less likely, an increase) in height growth due to leader damage. Various hypotheses can be tested through judicious formulations of D_{ij} . Similar research with lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex. Loud.) suggests that leader damage affects height growth for more than one year after the damage occurs (Nigh 2017).

Following this work, three hypotheses were tested:

(H1) Height growth is affected by the most recent leader damage within the current and last three years, but the effect is contingent on how long ago the event occurred;

(H2) Height growth is affected by leader damage in the current and last three years and the effect accumulates multiplicatively; and

(H3) Height growth is affected by leader damage in the current and last three years and the effect accumulates additively.

Variable D_{ij} was formulated as follows to test these three hypotheses:

$$(H1) \quad D_{ij} = \begin{cases} d_0 & \text{if the latest damage occurred in the current year} \\ d_1 & \text{if the latest damage occurred in the previous year} \\ d_2 & \text{if the latest damage occurred two years ago} \\ d_3 & \text{if the latest damage occurred three years ago} \end{cases}$$

$$(H2) \quad D_{ij} = d_0 \times d_1 \times d_2 \times d_3$$

$$(H3) \quad D_{ij} = 1 + d_0 + d_1 + d_2 + d_3$$

where d_k , $k = 0, 1, 2$, or 3 , is the change in height growth due to damage that occurred in either the current year ($k = 0$), the previous year ($k = 1$), two years ago ($k = 2$), or three years ago ($k = 3$). For hypothesis 1, D_{ij} equals 1 if no damage event has occurred in any of the years under consideration. For hypothesis 2, $d_k = 1$, $k = 0, 1, 2$, or 3 if no damage occurred in the current year, the previous year, two years ago, or three years ago, respectively. For hypothesis 3, $d_k = 0$, $k = 0, 1, 2$, or 3 if no damage occurred in the current year, the previous year, two years ago, or

three years ago, respectively. If d_k , $k = 0, 1, 2$, or 3 , is not significantly different from 1 (or 0 for hypothesis 3) at $\alpha = 0.05$ then there is no effect of damage on leader growth for that year and d_k is set to 1 (or 0 for hypothesis 3), effectively removing that parameter from the model.

The model was fit with the three definitions for D_{ij} by maximum likelihood with the nonlinear mixed effects procedure NLMIXED in SAS (SAS Institute Inc. 2011). The three models were evaluated with Akaike's Information Criteria (AIC, Burnham and Anderson 2002). Unless one model is clearly superior to the others, multi-model inference is done by averaging model predictions using Akaike weights (Burnham and Anderson 2002), where appropriate. The standard regression assumptions were evaluated as follows. The assumption that the mean of the residuals was zero was tested with a t-test and the assumption that the residuals are normally distributed was tested with the Kolmogorov-Smirnov test and q-q plots (Sen and Srivastava 1990). The assumption that the residuals had a constant variance was evaluated with a plot of the residuals against age. The Durbin-Watson test was used to test for serial correlation (Sen and Srivastava 1990) by tree. The Holm step-down Bonferroni adjustment (Bretz *et al.* 2011) was applied to the Durbin-Watson tests because multiple tests were made. Formal significance tests were carried out at $\alpha = 0.05$.

The effect of leader damage on site index was evaluated through simulation. Except for the 60 year old tree, each of the three fitted height growth models was used to predict and accumulate the height growth of each tree from the last recorded height and age of the tree until age 50. This gives three estimates of the apparent site index assuming that the tree does not sustain any further damage beyond the last measurement. The apparent site index for the 60 year old tree is the observed height at age 50. The true site index of each tree was estimated by predicting and accumulating its height growth from breast height age one until age 50 for each of

the three models, assuming that the tree does not sustain any damage. A weighted average of the three apparent site index estimates and the three true site index estimates was taken, using the w_i from Table 2 as the weights to reflect uncertainty about which model is superior (Burnham and Anderson 2002). Three models were fit to gain an understanding of how age and the number of leader damaging events affect site index. These models are:

$$(3) \quad SI_i = a_1 \times \hat{SI}_i + a_2 \times A_i + \varepsilon_i$$

$$(4) \quad SI_i = a_1 \times \hat{SI}_i + a_3 \times \#E_i + \varepsilon_i$$

$$(5) \quad SI_i = a_1 \times \hat{SI}_i + a_2 \times A_i + a_3 \times \#E_i + \varepsilon_i$$

where SI_i is the estimated true site index (m) for tree i , $\hat{SI}_i$ is the apparent site index (m) for tree i , A_i is the breast height age of tree i at the last height measurement, $\#E_i$ is the number of leader damaging events that tree i has sustained up to and including the last measurement, a_1 , a_2 , and a_3 are model parameters that are estimated from the model fitting analysis, and ε_i is the error term for tree i . If there is no trend in site index with age and there is no effect of leader damage on site index, then the model should collapse down to $SI_i = a_1 \times \hat{SI}_i$ with $a_1 = 1$. Any trend in site index with age and/or effect of leader damage on site index can be ascertained by analyzing the results of fitting models 3, 4, and 5.

Results

Fig. 2a, b, and c are histograms of the percentage of trees with incidents of leader damage by age, percentage of trees with incidents of leader damage by 1 m height class, and percentage of trees damaged by years before sampling, respectively. Note that for Fig. 2b, some trees were in a 1 m height class for more than one year because it took longer than one year for them to grow through a height class. Fig. 2a and c only show the proportion of trees that were damaged for ages up to 40 years old, as few trees had ages older than 40 to give meaningful percentages.

There does not appear to be any trend in incidents of leader damage with age and height; the incident rates are generally between 10 and 20% per age or height class. There may be a slight downward trend in the proportion of trees with damage as the years before sampling increases (Fig. 2c). The proportions for the older trees are not well-estimated due to decreasing sample sizes so this trend should be confirmed with more data. Table 1 lists the number of trees that sustained damage by the amount of damage, and also the number of trees that had damage that was detectable from a visual inspection after felling, also by the amount of damage based on the visual inspection. The number of incidents of leader damage per tree ranged from 0 to 15. About 67% of the trees had outwardly visible signs of damage that were not detected during the pre-harvest inspection. The number of incidences of outwardly visible damage ranged from 0 to 4.

Hypothesis 2 resulted in the model with the smallest AIC, followed by the model for hypothesis 3 and then hypothesis 1 (Table 2). Table 2 contains ΔAIC and the Akaike weight, w_i , (Burnham and Anderson 2002) for model i , where $i = 1, 2$, or 3 corresponding to the three hypotheses being tested. The w_i are considered to be the weight of evidence in favour of a model, given the set of models being evaluated (Burnham and Anderson 2002). Therefore, hypothesis 2 is the favoured hypothesis, with some support for hypothesis 3 and lessor support for hypothesis 1. There was no effect on height growth when damage occurred 3 years previously for all three hypotheses, i.e., parameter d_3 was not significantly different from 1 (for hypotheses 1 and 2) or 0 (for hypothesis 3). Successful convergence of NLMIXED could not be achieved with the random effect b_{1i} in the model; consequently, the model was fit without this parameter. Parameter estimates for the models based on the three hypotheses are in Table 2.

The analyses of the residuals are almost identical for the three fitted models. The means of the residuals are all approximately -0.0008 are not significantly different from 0. A plot of the

residuals against age indicates that the residuals are homoscedastic for all three models. The Kolmogorov-Smirnov test for normality indicates that the residuals are not normally distributed ($p = 0.013$, 0.019 , and 0.012 for the models testing hypotheses 1, 2, and 3, respectively) but the q-q plots in all cases shows that the non-normality is caused by a few observations at the tails of the distribution. The Durbin-Watson tests show that only three plots had significant serial correlation. Given that the violations of the normality and independence assumptions are minor, and that these violations do not bias the parameter estimates, no further action was taken to meet these assumptions. Graphs of the height trajectories of three trees are presented in Fig. 3 to give some indication about the fit of the model. The measured heights are represented by dots, the solid line represents the predicted height trajectory, and the dashed line is the predicted trajectory if the tree had not sustained any damage. The predicted height trajectories are the weighted average of the predicted heights from the three models under consideration using the w_i from Table 2 as weights. This was done because one model was not clearly superior to the others (Burnham and Anderson 2002). The tree in Fig. 3a is the oldest tree and it sustained the most damage (15 events). Fig. 3b is the height trajectory of one of the trees with a very good fit. This tree did not sustain any damage; consequently, the predicted and the predicted undamaged height trajectories are identical. Fig. 3c shows the height trajectory of a tree with 5 incidents of damage, two of which came at ages 11 and 12 and are clearly visible in this graphic. The fit of the model to this tree is also quite good.

The results of the tests for the effect of leader damage and age on the estimated site index based on height growth simulations (models 3 – 5) are in Table 3. The model that includes the apparent site index and both age and number of damage events as predictor variables results in the smallest AIC, followed by the model with apparent site index and number of damage events

but not age. The model with apparent site index and only age is a much poorer fit. Based on the w_i for these three models (Table 3), model 5 with apparent site index, age, and number of damage events is clearly superior ($w_i = 0.969$) (Burnham and Anderson 2002) and is the only model considered for this part of the analysis. The analysis shows that the apparent site index underestimates the estimated true site index with increasing age and number of damage events.

Discussion

This research shows that there are extensive amounts of leader damage in white spruce site trees that have passed an external examination for damage. This damage was not detected by the external examination because the damage had been overgrown by radial stem growth. Damaged trees are not site trees and hence should not be used to estimate site index. However, since the damage is unobservable, these trees were inadvertently selected as site trees. The selection of some of these trees with leader damage as site trees may be avoided by a more careful external examination of the tree stem from the ground. However, the field crews for this project were diligent in selecting the trees so unless an inordinate amount of time, effort, and expense is spent examining trees for external signs of damage, it is not feasible to totally eliminate these trees from the sample. Even if all external signs of damage were identified before sampling, still only 16% of the remaining selected trees were free of damage and hence were acceptable site trees.

The conclusions reached in this research conflict with those of Nigh and Love (1999), who concluded that the damage does not affect height growth. This research was specifically designed to address the issue of height growth reduction caused by leader damage whereas Nigh and Love (1999) were focused on the amount of damage. The analysis techniques applied here are better able to quantify height growth losses due to leader damage and are also able to detect

an increase in height growth after leader damaging events. The anecdotal observation by Nigh and Love (1999) that height growth increases after damaging events is not supported by this research; in fact, the opposite effect was found, that is, height growth is reduced after a damaging event.

In a similar study with lodgepole pine (Nigh 2017), leader damage was found to reduce height growth by approximately 35% in the year that the damage occurred and by 15% in the following year, with height growth returning to normal in the third year after the damage event. White spruce leader damage results in less height growth loss than lodgepole pine but the effect of the damage lasts longer (approximately a 28% reduction in the year of the damage event, then a 6 and 3% reduction in the following two years). The impact of leader damage on site index was not assessed for lodgepole pine in the Nigh (2017) study, but the larger reduction in height growth for lodgepole pine would presumably lead to a larger decline in site index. It is not clear why these two species respond differently to leader damage, but it could be related to the generally faster growth of lodgepole pine (Thomson and McMinn 1989).

Leader damage has a transient effect on height growth, but a long-lasting effect on site index. Leader damage reduces height growth by approximately 28% in the year that the damage occurred, by 6% in the following year, and by 3% in the subsequent year. Height growth returns to normal three years after the damage event. Based on the results of the simulations, each damage event reduces the site index by 0.16 m (Table 3, eq. 5). However, this does not fully explain the downward trend in site index with sample tree age (Fig. 1). There is still some other factor(s) that reduces site index as the tree ages (Table 3, eq. 5). These reductions in site index are specific to this data set. The realized reduction in estimated site index will depend on how many damage events occur, the age at which the tree incurs the damage, and the timing of the

events (three events in three years will cause less height growth reduction than if they were spread out over a period of time). As more damage events occur to a tree, the site index estimate from the tree becomes a poorer measure of the inherent site productivity.

The trees used to develop the models that predict the site indices in Fig. 1 have unknown amounts of leader damage and are no longer available for inspection. However, given the results of this research it seems assured that some of these trees had leader damage and hence did not come from the population of site trees. If that is the case, then the white spruce site index models developed from these trees do not model the height trajectory of site trees. Trees with more or less leader damage would follow different height trajectories than those implied by these models. This could explain some differences when site index models are compared to each other or when validated with independent data (e.g., Wang and Klinka 1995).

Our inability to definitively identify site trees from a visual inspection leads to some operational issues. Are the height trajectories of the site index model representative of site trees, or do they represent the height growth of trees with damage? If the latter, how much damage and when did the damage occur? How different are the height trajectories of damaged trees from the height trajectories of site trees? When applying the site index models to project height and/or estimate the site index from a sample tree, is the sample tree a site tree or does it have hidden leader damage and if so, how much? These issues could be addressed by harvesting the sample trees and splitting them to identify leader damage, but this is operationally prohibitive in terms of time and cost.

This research does suggest a potential solution for developing site index models for site trees with damage. Most site index models are developed by modelling height. However, trees that have leader damage but otherwise met the requirements for a site tree could be used to

develop site index models if height growth were modelled instead of height as was done here, and the height growth data for the year that the damage occurred and the two subsequent years were removed from the data set. This would come at the expense of optimizing for height growth instead of height, which is usually of more interest than height growth, and the loss of some data.

Nigh (2017) outlines three options for applying site index models using damaged site tree for lodgepole pine, and these options apply equally well for white spruce:

- 1) Accept that the site index estimate based on damaged trees will not reflect the potential productivity of the site. The effectiveness of this option will depend on how much damage is in the site tree, which will likely be unknown at the time of the application.
- 2) Devise an adjustment to the height of the site tree to account for leader damage. Again, the feasibility of this option depends on being able to evaluate the amount of leader damage in the site tree.
- 3) Skirt the issue by basing growth and yield estimates and silviculture prescription on site (ecosystem) type. British Columbian foresters have the BEC system on which to build this option.

Identifying the biotic or abiotic factors that may have caused leader damage was not an objective of this research. However, the damage was so extensive that it raises questions about its origin; the literature provides some clues. Frost and cold winter weather have been noted to cause bud mortality. Frost damage can lead to extensive terminal leader failure (Harding 1986). This occurs when early warm weather causes buds to partially open and allows moisture to enter the bud. The bud is killed if a frost subsequently occurs (Coates *et al.* 1994). Cold winter damage to buds has occurred if the cold weather follows considerably warmer than ordinary weather. It has been hypothesized that the warm early winter weather causes the buds to lose their cold

hardiness and then are killed if cold weather follows (van der Kamp and Worrall 1990). Several insects may cause the leader damage seen in this research. The spruce weevil (*Pissodes strobi* Peck) causes serious damage in younger spruce trees (Turnquist and Alfaro 1996). The spruce weevil kills two years of leader growth, which may account for the loss of height growth in the years following the damage event that was found in this research. However, spruce weevil is not a common pest in the regions where sampling occurred. The spruce bud moth (*Zieraphera canadensis* (Mut. and Free.)) can cause shoot damage that leads to leader breakage (Carroll *et al.* 1993). This species is found throughout Canada and the United States (Mutuura and Freeman 1966). The spruce bud midge (*Rhabdophaga swainei* Felt) attacks terminal buds which causes leader failure (Harding 1986) and can cause damage to significant numbers of white spruce trees (Cozens 1984). Cerezke (1972) simulated the type of damage caused by the spruce bud midge by removing the leader terminal bud and comparing the growth of these trees to control trees. Similar to this study, Cerezke found that leader damage reduced height growth by about 75% two years after bud removal, although a statistically significant height growth loss was only detected in the first year after bud removal. This study showed that height growth was reduced for three years. Differences in these two studies may be due to Cerezke's small sample size of 24 trees. Fig. 2c suggests that the damage is pervasive rather than episodic. Severe frost events and/or insect outbreaks that cause leader damage would presumably appear in Fig. 2 as large spikes in the histogram. While there are some spikes in the histogram, it is subjective as to whether these are large enough to indicate unusual events. Fig. 2c suggests that there may be a downward trend in the proportion of trees with leader damage as the years before sampling increases. This indicates that the damage rates are increasing over time regardless of tree height or age, making climate change a candidate for causing for this trend. Climate change can result

in more extreme weather events such as wind storms and late frosts, and can lead to insect outbreaks (Kirilenko and Sedjo 2007), all of which can cause leader damage. This experiment was not designed to identify the cause of leader damage; this may be an area for future research.

This research raises the philosophical question of whether frost is a site effect. Soil and climate are major factors that influence tree growth (Monserud 1988). Consequently, the influence of climate on tree growth should be captured in site index. However, it is important to make a distinction between climate and weather. Frost, and also wind storms, are weather events and hence should not be captured by site index. Incorporating the effects of frost or wind damage into site index would be difficult and applying such a measure would be next to impossible as future frost and wind events would have to be assumed or forecast. Furthermore, including loss of height growth from frost or wind damage in site index seems to go against the intent of site index, which is a measure of the potential productivity of a site.

Conclusion

White spruce trees that are identified in the field by a visual inspection as being site trees have large amounts of leader damage that is hidden by radial stem growth, which makes the trees unsuitable as site trees. The damage is likely caused by frost or insects. Trees with leader damage have reduced height growth by approximately 28% on average in the year that the damage occurred, and by 6% and 3% in the two years following the damage event. Estimating site index with trees with leader damage will underestimate the inherent productivity of the site and could be contributing to the trend in site index seen in the SIBEC data. Site index models that are developed with trees that have hidden leader damage will have biased site tree height trajectories.

Acknowledgements

Funding for the data collection was provided by the Land Based Investment Strategy of the British Columbia Ministry of Forests, Lands and Natural Resource Operations. I thank Ken White (British Columbia Ministry of Forests, Lands and Natural Resource Operations) and Allan Carroll (University of British Columbia) for valuable assistance on identifying potential forest health agents that might be causing the leader damage. Peter Ott, Graham Hawkins, and Ken White with the British Columbia Ministry of Forests, Lands and Natural Resource Operations provided valuable review comments on an early draft of this manuscript. I thank two anonymous reviewers and the associate editor for review comments that improved the manuscript.

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- 506

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507 **Table 1.** Number of trees by number of incidents of damage, before and after stem splitting.

# of incidences of leader damage	Number of trees with detected damage	
	Before splitting	After splitting
0	38	6
1	32	12
2	24	18
3	16	19
4	5	18
5		17
6		6
7		6
8		4
9		3
10		1
12		4
15		1

508

509 **Table 2.** Parameter estimates, their standard errors, AIC, Δ AIC, and w_i for the models based on
 510 the three hypotheses.

Parameter	Hypothesis 1		Hypothesis 2		Hypothesis 3	
	Estimate	Std. err.	Estimate	Std. err.	Estimate	Std. err.
a_0	31.14	1.16	31.08	1.15	31.03	1.15
a_1	0.03109	0.00148	0.03118	0.00148	0.03121	0.00148
a_2	1.540	0.0360	1.541	0.036	1.541	0.0360
d_0	0.7122	0.0110	0.7232	0.0107	-0.2724	0.0106
d_1	0.9370	0.0128	0.9416	0.0118	-0.05450	0.0112
d_2	0.9710	0.0137	0.9713	0.0120	-0.02565	0.0113
$\text{Var}(b_{0i})$	19.69	3.72	19.59	3.69	19.46	3.67
$\text{Var}(b_{2i})$	0.05084	0.00964	0.05076	0.00963	0.05070	0.00962
$\text{Cov}(b_{0i}, b_{2i})$	0.3988	0.134	0.4003	0.134	0.3981	0.133
$\text{Var}(\varepsilon_{ij})$	0.1100	0.00321	0.01099	0.00320	0.1099	0.00321
AIC	-3894		-3898		-3897	
Δ AIC	4		0		1	
w_i	0.078		0.574		0.348	

511

Table 3. Results of the analysis of models 3, 4, and 5.

Model	Fitted equation	AIC	Δ AIC	w_i
3	$SI = 0.9879 \times \widehat{SI} + 0.0381 \times A$ (0.0050) (0.0042)	138.1	250.2	0.000
4	$SI = 1.0006 \times \widehat{SI} + 0.1719 \times \#E$ (0.0010) (0.0044)	-105.2	6.9	0.031
5	$SI = 0.9947 \times \widehat{SI} + 0.0073 \times A + 0.1588 \times \#E$ (0.0016) (0.0017) (0.0050)	-112.1	0	0.969

Note: These models test for the effect of leader damage and age on site index. The models are presented along with their AIC, Δ AIC, and w_i . The standard error of the parameter estimates are in parentheses below the parameter estimate.

516 **Fig. 1.** White spruce estimated site index trend over time. Dots represent the estimated site index
517 from a sample plot and the line represents the trend in site index as determined by segmented
518 regression.

519

Fig. 2. Histograms of percentage of trees with leader damage detected after splitting the trees by age class (part a), height class (part b), and years before sampling (part c).

524

525

Fig. 3. Height trajectories of three trees chosen to demonstrate the fit of the model to the data. The dots are the measured heights, the solid line is the predicted height trajectory, and the dashed line is the predicted height trajectory assuming that the tree did not incur any leader damage. The tree in part a) had 15 damage events to the leader whereas the tree in part b) did not have any leader damage. The tree in part c) experienced five leader damaging events.