Short and Long Term Management Strategies for Western Spruce Budworm in British Columbia in the Face of Climate Change

Graduate Thesis FRST 497

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ABSTRACT

Western spruce budworm (Choristoneura occidentalis Freeman) is a dominating defoliator species in British Columbia’s Douglas-fir forests, and perceived changes in outbreak ranges have become a point of concern for forest managers. This paper is a response to this concern, and aims to contextualize the mechanism and spread of this defoliator’s range within historical context and within a future for forests that will alter with climate change. A summary of the available short-term and long-term management responses to pest outbreak was made. These tables discuss short-term and long-term management strategies for forest health in terms of the forest industry, to forest ecosystems, and how climate change will affect these strategies. With this contextualized understanding of western spruce budworm, integrated management ought to include consideration for multiple pest species and chemical treatment should be considered as a viable solution to combat outbreak.

Key words: outbreak, management, climate change
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Introduction

Topic

Forest managers in the Interior Douglas Fir (IDF) biogeoclimatic zone of British Columbia are routinely faced with complex biotic disturbances that occur in their stands, a notable one being the western spruce budworm (*Choristoneura occidentalis* Freeman) (Harris et al. 1995; Maclauchlan & Brooks, 2009; Murdock et al. 2013). While insect outbreaks in managed stands are a cause of concern for people and communities dependent on the quality of timber produced from those stands, it would be a misconception to focus efforts on eradicating these disturbance agents (e.g. through intensive insecticide methods). Rather, management strategies should be informed on historical western spruce budworm population cycles as well as studied outcomes of the various current responses and integrated pest management plans that are being used in British Columbia’s IDF forests. The mechanisms used in other similar regions of the world that face western spruce budworm outbreaks may also be useful to apply in this province.

Problem statement

Due to regions of BC experiencing extensive western spruce budworm outbreaks recently, particularly in the central interior forests (Axelson et al. 2015), there is a perception that these events are unprecedented, and that coupled with climate change they may lead to an expansion of this defoliator’s range into northern parts of the province. If a forest manager’s response to this is to attempt extensive insecticide treatments to their stands, there may be more harm to forest health and industry stability than anticipated.

The objective of this paper is to consolidate a summary of the state of British Columbia’s forest health with regards to western spruce budworm in IDF BEC zones. In particular, this paper will discuss short-term and long-term management strategies for forest health in terms of 1) the implications to the forest industry, 2) the implications of these strategies to forest ecosystems, and 3) how climate change will affect these strategies. It will explore the historical trends in forest health until the present day in order to contextualize the presently observed widespread outbreaks, so as to respond with more informed management decisions in the aim of creating robust integrated pest management plans.
This paper will explore a topic that is relevant to many types of forests in British Columbia and many forms of insect disturbances. However, for the purpose of focused discussion, the scope will only include the forest management strategies related to the western spruce budworm in Douglas-fir dominant forests. Eastern spruce budworm will not be considered in the integrated management plans. Fire will be mentioned briefly, but will not be discussed in depth as a possible controlling strategy. Other species of pests and other BEC zones will not be examined in depth, as they would fall outside of the intentions of this study, although some will be used as examples of synergistic effects of pathogen dynamics in stand disturbances. Furthermore, the management of non-timber forest products that exist within this specified zone will not be addressed, although they are pertinent to the ecology and economy of communities that rely on the timber from these IDF forests.

Background

**Western spruce budworm biology and its impact to trees**

Adult western spruce budworm lay eggs under the needles of the host trees in summer, and the eggs hatch about 10 days later (1st instar). After molting once, the larvae hibernate on the bark surface throughout winter (2nd instar) (Dekker-Robertson et al., 2004). The larvae emerge in the spring and burrow into overstory foliage or float on silken threads to land on new buds (3rd instar). The emergence date is most dependent on air temperature, but western spruce budworm have developed flexibility in their emergence so as to synchronize more with bud burst (Campbell et al. 2006). The larvae consume older foliage and continue until reaching the period in spring/early summer during bud break (4th - 6th instar). This dispersal occurs mostly between older overstory trees towards younger understory trees, which is a significant contributor to outbreak severity since weakened younger trees will result in forest stands that are less resilient to prolonged attacks and stressors (Fegyverneki, 2012). By summer the larvae retreat into the silk-needle shelter (pupae) and emerge after completing pupation. The cycle starts over as the adults emerge and fly to seek a mate (Dekker-Robertson et al., 2004).
Western spruce budworm ideal growth conditions

Roberts & Weatherby (1997) state that pest outbreaks need to be understood within boundaries that distinguish them from an endemic-level population size. These include knowing the tree susceptibility and tree mortality rate at endemic levels of infestation, and comparing them to occurrences of epidemics where these following parameters have been defined: 1) the outbreak trigger, 2) the duration and intensity, and 3) the frequency of the outbreak.

The trend in spruce budworm outbreaks is for them to occur in Douglas-fir forests that had higher mean annual temperatures, lower temperature differences between the coldest and warmest months, fewer days below freezing temperatures, lower summer precipitation and higher summer: heat moisture index than the average IDF climatic conditions (Forest Practices Code of BC, 1995; Nealis, 2012).

Western spruce budworm hosts and range

Western spruce budworms target certain species within the interior Douglas fir BEC zone: Douglas fir (Pseudotsuga menziesii var. Glauc Beissn. Franco), true firs (Abies spp.), Engelmann spruce (Picea engelmanni Parry ex Engelm.) and western larch (Larix occidentalis Nutt.), although the species most associated to outbreaks in BC is Douglas fir (Dekker-Robertson et al. 2014).

The presence of western spruce budworm outbreaks has been recorded in the southern interior forests of BC since the beginning of the 20th century and verified using dendrochronological analysis (Harris et al. 1985; Swetnam & Lynch, 1993). Western spruce budworm presence has also been inferred in more northern regions of the province, such as the Cariboo Forest Region in the central interior, due to patterns pointing to widespread reduced radial growth in trees during cyclical periods of time (Westfall & Ebata, 2011). It should be noted that since there are many assumptions associated with the methods used to determine the insect’s habitat range, researchers suggest that dendrochronology analysis alone cannot determine 'unprecedented' range expansion (Axelson et al. 2015).
Characteristics of forest BEC zone of interest: Interior Douglas-Fir

Meidinger and Pojar (1991) have described the biogeoclimatic ecosystem (BEC) zones of British Columbia. The Interior Douglas Fir zone occurs in the rain shadow of the Coast Mountains, at different interior valleys such as the Fraser, Thompson, Similkameen and Okanagan. It is the second warmest forest zone, and is characterized by long warm dry summers and short cool winters. This produces a landscape of rolling hills with dry bluebunch wheatgrass and rough fescue meadows interspersed with patches of forests. At higher elevations, the mature forests tend to be predominantly dense Douglas-firs, while lodgepole pine tends to establish first after disturbances.

South facing slopes in the lower elevations in these areas attract many wildlife species such as Mule Deer, Bighorn Sheep, and non-migratory passerine birds that seek shelter in the winter. While the Douglas-fir forests act as the winter range for many grazing species, the thick grassy fields provide shelter for birds and small mammals.

In the lower elevations of the southern interior parts of this zone, the forests grade into Ponderosa Pine BEC zones, while wetter areas transition into Interior Cedar Hemlock. At higher elevations, the IDF grades into the Engelmann Spruce Subalpine Fir zone. As for IDF that occurs in the central interior, the low elevation forests transition into Bunchgrass zone, the higher elevation forests into Sub-boreal Spruce.

Natural regulating factors

Budworms are naturally regulated by density dependent factors such as insect parasites, vertebrate and invertebrate predators such as spiders, chipmunks, birds, and also by abiotic, density independent factors such as extreme cold. However, these factors combined do not help reduce population surges when the climate and forest stand conditions are ideal for reproduction and survival and population sizes reach epidemic levels (Fellin & Dewey, 1982).
Outbreak mechanisms

Campbell et al. (2006) outline the mechanisms of forest disturbance from these outbreaks as the following: certain climatic and ecological conditions allow for higher reproduction and survival rates in western spruce budworm populations. In addition, stand structures with overlapping canopies may facilitate the dispersal and spread of infestation. When this occurs to the point where insect population is high enough, there is reduced annual growth during years of active defoliation and the following years after feeding has stopped (Westfall & Ebata, 2011). At this point if infestation, visible foliage damage can be observed overhead in forest stands because the trees do not have enough time to recover, and the outbreak has spread across the forest stand.

Factors contributing to contemporary western spruce budworm outbreaks

Though the historical presence of western spruce budworm and other defoliators in British Columbia has been acknowledged by many researchers (Axelson et al. 2015; Marciniak, 2015), it is in fact past forestry practices which have contributed the most to the extent of these currently observed outbreaks (Burleigh et al., 2002; Maclauchlan & Brooks, 2009). These forestry practices include selective harvesting of ponderosa pine, increased fire suppression, and restoring harvest sites to multi-layered canopies with a thick understory (Forest Practices Code of BC 1995).

MacLauchlan and Brooks (2009) found that in stands where trees in the understory experienced high regeneration due to selective harvesting also experienced the highest mortality. This was attributed to mature overstory trees providing sustained older foliage for larvae to feed on while suppressed understory trees provide fresh young foliage. As these younger trees experience more stress from defoliation, their mortality increases. Canopy structure contributes most to outbreak severity as it is the main dispersal mechanism for the budworm larvae to access young understorey foliage (Forest Practices Code of BC, 1995). The authors attributed this mismanagement to stands which have not been pruned or thinned and have resulted in high-density stands which facilitate western spruce budworm growth and distribution. The duration and frequency of outbreaks are most attributed to climatic
conditions that regulate budburst, predominantly air temperature (Forest Practices Code of BC, 1995).

**Breakdown of western spruce budworm impact/toll by forest regions in the province**

A survey of forest insect and disease conditions conducted by the Canadian Forest Service, Forest Insect and Disease Survey (FIDS) in 1985 found that since the early 1900s, approximately 60% of BC’s 4.5 million ha of Douglas-fir dominated stands have been impacted by western spruce budworm infestations, and the region with the highest frequency was Pemberton, which had at least 4 outbreaks in the span of 80 years (Harris et al., 1985). FIDS surveys first began in the 1950s and by the end of the century; 200,000 hectares of forests were affected by western spruce budworm outbreaks in the interior. As of 2003, this number had increased to over 500,000 hectares (Maclauchlan et al., 2006; Westfall and Ebata, 2011).

In a simulation using parameters that replicate western spruce budworm outbreaks in different future climate projections in Okanagan Forest Region, Murdock et al. (2013) found that at the base scenario (or in a projected future climate that is the same as current conditions) there is an expected 300,000 mil m³ volume decrease from the current 2.6 million m³ annual allowable cut. With both future climate projections that are warmer/wetter or hotter/drier than current conditions, there was an even larger projected decrease in harvest volume. This dramatic reduction in future forest yields will undoubtedly exacerbate the currently weakened forestry economy, with local industry-driven communities being affected the most.
Techniques used to study outbreak history and determine trends

There are several approaches to studying insect outbreaks in forests. The first is by using dendrochronology, which examines the tree-rings of individual trees found in an infested stand. This allows researchers to track periods in the tree's growth which express the magnitude and frequency of disturbance events (Campbell et al. 2006). Generally, the cores from Douglas fir samples are cross-referenced with similarly aged, western spruce budworm-resistant Ponderosa pine cores to determine if the patterns of tree ring size change are due to growing conditions or to insect defoliation (Campbell et al. 2006).

Another method is to use aerial surveys and spectral analyses, which include photography or remote sensing, to determine the extent and severity of foliage damage at a landscape level (Marciniak 2015). This can then be cross-referenced to aerial data from other known outbreak periods to determine patterns.

Finally, models can be created based on characteristic behavior traits associated with spruce budworm outbreaks, such as low-frequency oscillations every 20-40 years, high frequency sawtooth oscillations every 4 – 7 years associated with timings of reproduction and dispersal, and outbreak styles which alternate between stand replacing and non-stand replacing (Murdock et al. 2013). These models are an aggregation of historical and current population and climatic data, which help project future stand health scenarios, especially those in relation to climate change (Sturtevant et al. 2015). Combined with tree species abundance data or data sets of harvestable locations, models are a powerful tool to help forest managers identify and prepare for the possible future scenarios and the risks involved (Murdock et al. 2013).

To reconstruct the historical presence of western spruce budworm outbreaks, researchers often use a tree-ring program called OUTBREAK since it allows the input of user-defined criteria (Sturtevant et al. 2015). These criteria tend to include standardized ring-width series which are ‘corrected’ based on a particular threshold for reduced growth, reaching below a certain standard deviation in this reduced growth, and measuring positive growth pre- and post-outbreak years (Axelson et al. 2015).
Climate change and its role in facilitating outbreaks range, timing and duration

In studies of the factors affecting budworm outbreaks in the 20th century, climate has proven to play a strong role in outbreak duration. The cycles of annual precipitation and air temperature changes influence the timing of western spruce budworm outbreaks, particularly how populations may synchronize in their growth and development. The pattern that was found to assist in population synchronization in IDF forests was to have large outbreaks during years of early spring temperatures and dry winters. These are believed to facilitate early budworm emergence, resulting in higher over-winter survival rates and an increase in vulnerability of Douglas fir trees against defoliation due to longer available feeding periods (Campbell, Smith & Arsenault 2006).

Axelson, Smith, Daniels, & Alfaro (2015) were able to pinpoint certain periods in the 20th century where outbreaks of variable size and locations demonstrated synchrony. These patterns of outbreak coincided with annual precipitation below 200 mm/year and when the mean annual temperature exceeded the average by 0.6 °C in the 1930s and 2.1 °C in the mid-1980s. With this larger perspective in mind, some researchers suggest that the observed outbreaks in the past 40 years should not alarm forest managers about unprecedented levels or ranges in western spruce beetle infestation. Outbreaks lasting around 14 to 18 years are a common occurrence, so concern that the outbreak range for western spruce budworm expanding northwards to the Cariboo Forest Region is also unfounded.

On the other hand, Marciniak (2015) and other studies (Burleigh et al. 2002) concluded that western spruce budworm’s northern trend for outbreaks in the past century were real. They determine this trend based on combined use of dendrochronology and aerial overview surveys. Marciniak compared stands that had historical recordings of insect presence that dated back one hundred years to contemporary aerial images. If these stands still have defoliation detectable from aerial survey, they are classified as experiencing a western spruce budworm outbreak. Otherwise, if the stand has recorded presence of pest infestation but no detectable stand defoliation, the researcher claims that it is not sufficient to call the presence of western spruce budworm defoliation in the tree rings an ‘outbreak’, nor
can proper synchrony between populations be established, since population sizes can’t be estimated from dendrochronology alone (Swetnam & Lynch, 1993; Marciniak 2015).

**Using climate projection modeling**

In a study of potential future forest climate scenarios by Murdock et al. (2013), the risk posed by increased air temperature and variable precipitation levels is not consistent in all regions of BC’s IDF forests. They chose two possible future climate projections out of a range of potential outcomes 20, 30 and 50 years into the future. These two climatic projections were where future conditions were warmer and wetter, or hotter and drier. In a future with warmer and wetter climate, budworm outbreak risk in the central and northwest of the province is expected to increase while in the southern interior valleys are expected to go from high to medium risk. As for a future climate projection of hotter and drier growing conditions, there is a smaller area in the province that shows increased risk of outbreaks compared to the first projection.

**Pest Management Strategies**

The Forest Practices Code of BC (1995) describes pest management strategies as the objectives or general plans that forest managers develop to control the level of insect disturbance on forest health. Management tactics are the implemented actions that are chosen to carry out the strategies. These strategies can have a short term or long term intention.

Short-term management strategies include direct control strategies that protect the foliage and reduce the population size by utilizing chemical or biological insecticides. Their effects can be observed soon after utilizing the tactic, and are generally relied on for immediate threats. Long term management strategies can include planting resistant trees, reducing high stand density, decreasing species composition, increasing tree vigor and decreasing understory trees. These generally require more time before having observable outcomes (FPCBCA, 1995).
Table 1 and 2 summarize some of the current management tactics available for short term and long term pest control strategies, respectively. These various tactics have been chosen to showcase the variety of potential options that forest managers may use to treat an infested stand or do preventative control (USFS, 1982; Blackford, 2004; Dekker-Robertson et al., 2014). Currently British Columbia does not employ all the listed tactics, since many of them are obtained from forest management practices across North America and the used in some states or provinces may not be available or allowed in others. Despite actual legislations for or against certain forest management practices, the ones listed below are meant to describe the currently used tactics and potential new tactics for forest managers in BC.

The range of tactics in table 1 show pest control options which emphasize the insect and directly controlling its numbers and manipulating the spruce beetles’ biology directly, whereas the range of tactics in table 2 are focused on how operational forestry can include harvesting and silvicultural practices which facilitate either tree health or hinder insect distribution and other population dynamics.
Table 1: Summary of possible short-term management strategies that are known to regulate western spruce budworm infestation. These various options are compared against the following categories: application details, ecological and economic consequences, and the relative success in the face of climate change. This table represents potential options for forest managers, but may be limited in their actual application due to lack of research or current legislations which do not allow for certain management practices (particularly chemical insecticides) to be used in operational forestry.

<table>
<thead>
<tr>
<th>Management Tactic</th>
<th>Description</th>
<th>Application Details</th>
<th>Ecological Consequences</th>
<th>Economic Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rearing natural predators</td>
<td>Use irregularly shaped cutting techniques to promote growth of these predators.</td>
<td>Specific to pest organism so no alteration of other insect species; no efficacy lag for the affected tree; may create competition for natural predators of western spruce beetle if they are present at outbreak site.</td>
<td>Minimal impact; safe to use in areas close to campgrounds and along streams or rivers.</td>
<td>Very expensive to rear and organize logistics of release.</td>
</tr>
<tr>
<td>Natural, host-specific parasite to lepidopterous insects</td>
<td>A form of foliage protection; directly enters the integument of the insect and kills them.</td>
<td>Application between 5-20°C.</td>
<td>Dependent on changing climatic regime will alter when and how &lt;1,4,8,9,10,20 can be applied</td>
<td>Excellent performance, but may be limited by changing growing conditions for host trees.</td>
</tr>
<tr>
<td>Chemical insecticides (e.g. Bacillus thuringiensis (B.t.k.))</td>
<td>Aerial application has more coverage and is more economical for large forest areas; requires regular monitoring to determine outbreak stage.</td>
<td>Applied at early stages of an outbreak.</td>
<td>Acephate has lower toxicity/residue in foliage after 2 weeks of application.</td>
<td>Growing conditions for these natural predators may change (if growing conditions for host trees change, likelihood of growing conditions not meeting the needs of the predators).</td>
</tr>
<tr>
<td>Biological augmentation</td>
<td>Managed in the field, and kills them.</td>
<td>Aerial application of the insecticidal protein. Directly impacts larvae of the pest.</td>
<td>No heavy rain for 48 hours prior to application.</td>
<td>Application details (e.g. sprays, timing, etc.)</td>
</tr>
</tbody>
</table>
Table 2  Summary of possible long-term management strategies that are known to regulate western spruce budworm infestation. These various options are compared against the following categories: application details, ecological and economic consequences, and their relative success in the face of climate change. This table represents potential options for forest managers, but may be limited in their actual application due to lack of research or current legislations which do not allow for certain management practices (genetically selecting trees) to be used in operational forestry.

<table>
<thead>
<tr>
<th>Management Tactic</th>
<th>Description (method, details)</th>
<th>Application details</th>
<th>Ecological consequences</th>
<th>Economic consequences</th>
<th>Success relative to climate change</th>
</tr>
</thead>
</table>
| Artificially selecting genetically superior trees for resistance to defoliation and density control to promote growth of superior/resistant tree and select from its cones. Requires progeny testing and genetic testing. Selection done in a nursery; reduces genetic diversity of insecticide. | Use stock and density control to promote growth of superior/resistant tree and select from its cones. Requires progeny testing and genetic testing. Selection done in a nursery; reduces genetic diversity of insecticide. | Use natural resistance to defoliation instead of introducing unnatural budworm insecticide. Introduces chemicals to forest systems. | A very long-term commitment; expensive. Improved tree health results in increased timber yields. May facilitate forests becoming carbon sinks because trees sequester more climate 
change. | Trees selected for resistance to current pest issue may not be adaptable to changing climate envelope. | May facilitate forests becoming carbon sinks because trees sequester more climate change. |
| Fertilization | Increase tree vigor by providing additional nutrition. | Increase tree vigor by providing additional nutrition. | Improved tree health results in increased timber yields. | May facilitate forests becoming carbon sinks because trees sequester more climate change. | |
| Replant with non-host species | Prevent overstory becoming breeding ground and source of dispersal of western spruce budworm and maintain multiple non-host species in layered canopies. | Prevent overstory becoming breeding ground and source of dispersal of western spruce budworm and maintain multiple non-host species in layered canopies. | Will change forest dynamics because of trophic interactions of dependent animals. | Could create potential site degradation; may have regeneration delays. | Success of replanting with different tree species depends on change in climate envelope and growing conditions. |
| Thinning and spacing | Prevent overstory breeding ground of western spruce budworm and maintain multi-layered canopies for lodgepole pine, western larch, etc. | Prevent overstory becoming breeding ground and source of dispersal of western spruce budworm and maintain multiple non-host species in layered canopies. | | | |
| E.g. western red cedar, lodgepole pine, western larch, Can maintain multi-layered canopies in traditionally IDF zone | | | | | |

This table represents potential options for forest managers, but may be limited in their actual application due to lack of research or current legislations which do not allow for certain management practices (genetically selecting trees) to be used in operational forestry.
**Discussion**

**Versatility in studying western spruce budworm**

An advantage to studying the nature of western spruce budworm outbreaks is the similarity that this system has to other defoliator pest systems, thus allowing for transferability of results to other species of interest. By using western spruce budworm outbreaks to study factors such as synchronization factor, population cycling behavior, and the link of defoliation to growth reduction and mortality in trees, more light can be shed onto other defoliator systems which share these common traits (Sturtevant et al. 2015).

**Integrated Pest Management and Forest Management Plans**

A successful integrated pest management plan should consider the complex interactions of biotic and abiotic factors within an ecosystem. As such, other defoliating pests associated with western spruce budworm ought to be studied and included in these management plans since their combined infestation could worsen the tree mortality level if left untreated, such as the Douglas-fir beetle.

Marciniak (2015) explains that with Douglas-fir beetles (*Dendroctonus pseudotsugae*), a common bark beetle in BC’s IDF forests, their long term infestation in mature overstorey trees could lead entire stands to high mortality that have already been hit by western spruce budworm, which in turn increases the vulnerability of younger understory trees to infestation. In this situation, the combination of the two infestations leads to a synergistic impact on forests, which can be described as the two stressors having more effect than if the sum of their separate impacts were calculated together. With this in mind, forest managers ought to consider how interactions between forest pest species or other trophic interactions can result in changes in the biodiversity and dynamics of the greater ecosystem.

Major periodic defoliators Douglas-fir bark beetle and Douglas-fir tussock moth have responded positively to warming temperatures and changes in precipitation (Westfall & Ebata, 2010; Murdock et al., 2013). It is likely that there will be northward shifts and increased severity, duration, and synchrony of Douglas-fir beetle populations as a result of
western spruce budworm outbreaks expanding northward and to higher latitudes (Marciniak 2015).

This prediction corresponds to northern latitudes experiencing growing seasons that support western spruce budworm survival and growth, while also providing forests with growing seasons that can facilitate the transition of northern/interior BEC zones into commonly southern BEC zones. As these successional zone transitions will occur at a slower pace than outbreak cycles, more emphasis should be put on targeting budworm populations that currently exist in Douglas fir stands.

Given the above research on how western spruce budworm outbreaks facilitate further vulnerability of forests to other insect infestations, short-term management strategies should strongly consider the possibility of chemical treatments of harvestable forest stands. This essentially removes the link between western spruce budworm and other defoliators, which exacerbate the effect of defoliation. Replanting harvestable stands with non-host species allows for long-term management plans to achieve better forest health. Diversity in tree species allows for breaks between dispersal from overstory spruce to understory spruce, thus lessening the extent of the outbreak.

**Recommendations to improve current research**

While current research on western spruce budworm has explored and revealed the complex nature of this forest insect, there are still many areas of research to develop further or improve on, particularly when an integrated pest management plan is being considered. Murdock et al. (2013) suggest that researchers should broaden their scope in understanding disturbance regimes, and avoid a research approach that is too narrow. In addition, these multiple species research should aim for a 600 m resolution for the timber supply areas, as this would give forest managers more relevant information at an operational level. Their final recommendation is to include outbreak data from the southern extent of the forest regions where western spruce budworm presence is higher, since this will avoid misinterpreting any data as having an ‘unprecedented’ scale without seeing the larger landscape.
Ultimately, these improvements in spatial analysis of western spruce budworm presence and distribution in forests will better classify whether the forest is experiencing an outbreak and more appropriate management tactics can be used with this improved knowledge. In addition, improved spatial monitoring can inform how effective the short term and long term management tactics are in either preventing or controlling budworm population sizes.

Climate change is an integral part of a forest manager’s consideration when determining operational measures on their land. While the uncertainty involved may be daunting, continued research into the potential effect of climate change on how trees and dependent species will adapt is necessary and will help inform decisions that will maintain the forests’ viability and integrity. It is not enough to only ask how drastic climate change will affect forest dynamics, but that the nature of the interactions should also be examined, such as whether biotic disturbance agents will intensify their impact on forests in an additive, synergistic or antagonistic way (Marciniak 2015).

As climate change is also a global phenomenon, the scale of research needs to extend as well to include long-term landscape changes due to outbreaks. A question that Marciniak poses with regards to climate change is whether there will be a difference in behavior for western spruce budworm, since at low population levels they have been documented to attack tree species outside their natural range. Could climate change add pressures for the pathogen to expand the species range that it normally targets?

**Limitations or assumptions in western spruce budworm research**

Several common issues exist in nearly all research that is conducted on western spruce budworm outbreak modeling, ranging from the modeling process to intrinsic qualities of western spruce budworm populations. Sturtevant et al. (2015) summarized the first issue very clearly, in that modeling budworm population dynamics and growth can never be possible for real-time, operational scales because the resolution necessary (clear imagery at a scale of 1:600m) is too expensive to be feasible for all regional forest managers in the province. Management decisions will have to continue to rely on the current practice of using
spruce budworm decision support system (SBDSS) which combine annual defoliation scenarios into a cumulative five-year defoliation to predict the impact that western spruce budworm population changes will have on tree growth and stand mortality, using a GIS forestry inventory database. Long term tactics that depend on the change of forest structures to fertilization, harvesting styles, silvicultural changes, or transitions in BEC zones can be integrated into these SBDSS so that predictions of impacts can account for the changes in tree vigor and changes in possible distribution of the insects.

The second issue related to the modeling process is how user-defined criteria for outbreak modeling generally have to omit important forest dynamic influencers and tree dispersal rates, which inevitably cause predicted climatic envelope models to be overestimates (Murdock, Taylor et al. 2013). Along the lines of omissions that skew the results of models, the tree species that are studied in outbreak models do not represent all species that will be affected by either western spruce budworm or climate change. As such, forest managers who are responsible for the diversity and ecological integrity of their forests need to consider the broader interactions of tree species and their roles in the dynamics of species interactions, how these will respond to outbreaks, and how harvest levels will depend on the availability of merchantable timber (Murdock, Taylor et al. 2013). This is linked to certain long term management tactics as the current operational procedure in BC forests is to cultivate stands that are most economically profitable, yet many of the long term management tactics call for possible complications to harvest practices, particularly when introducing new tree species or requiring certain stand structures.

Another important factor that hinders research on western spruce budworm management strategies is the particularly long life cycle lengths that outbreaks have (at least a decade long), which exceed most scientific careers. With regular turnovers on long-term budworm monitoring projects, there is little likelihood of fully measuring the extent of an outbreak from its onset to its completion, or how successful the management plan implementations were in a region (Sturtevant et al. 2015).
Bibliography


