Forest health and climate change: A British Columbia perspective

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ABSTRACT

BC's forests have already faced two simultaneous, globally significant, epidemics linked to climate change; the Dothistroma needle blight epidemic in NW BC and the massive mountain pine beetle epidemic throughout the BC Interior. Building on these experiences, we have compiled our best estimates of how we believe other forest health agents may behave as climate change continues to influence our forests. We have drawn on literature from around the world but have focused on the situation in BC. We have made management recommendations based on what we have seen so far and what we expect to come.

Key words: climate change, forest health, forest insects, forest pathogens, forest management, British Columbia

RÉSUMÉ

Les forêts de la C.-B. ont déjà subi simultanément deux épidémies significativement importantes liées aux changements climatiques : la brûlure en bande rouge à l'état d'épidémie dans le nord-ouest de la C.-B. et l'infestation massive par le dendroctone du pin ponderosa relevé partout dans la zone intérieure de la C.-B. À partir de ces situations, nous avons bâti nos meilleurs estimés de ce qu'il nous semble sera le comportement d'autres ravageurs forestiers alors que les changements climatiques continuent de modifier nos forêts. Nous avons consulté des documents de partout dans le monde, mais nous nous sommes attardés à la situation vécue en C.-B. Nous avons établi des recommandations portant sur l'aménagement d'après ce que nous avons constaté à ce jour et selon ce que nous prévoyons pour l'avenir.

Mots clés : changements climatiques, santé des forêts, insectes forestiers, pathogènes forestiers, aménagement forestier, Colombie-Britannique

Introduction

The earth's climate is entering a period of rapid change due primarily to human activity and the burning of fossil fuels (IPCC 2007, McMullen and Jabbour 2009). The resulting alterations in temperature and precipitation patterns will have a direct impact on both natural and modified forests (Kirilenko and Sedjo 2007) and are expected to produce large shifts in vegetation distributions at unprecedented rates (Allen and Breshears 1998). These climatic changes could result in improved forest productivity (Aber *et al.* 2001); however, increases in the frequency and intensity of wildfires, severe wind-throw events and outbreaks of insects and pathogens, may be more important than any positive influences of warmer temperatures and elevated CO_2 (Kirilenko and Sedjo 2007). Climate change-related forest vegetation shifts will be facilitated, if not driven, by wildfires and other natural disturbance agents including insect and disease outbreaks (Dale *et al.* 2001). The most responsive species, those with short life spans and rapid regeneration rates, like insects and pathogenic fungi, are likely to be more positively affected by climate change than their long-lived hosts (Ayres and Lombardero 2000).

The climate has changed many times over the millennia (IPCC 2007). It is the rate at which the climate is currently changing, and from the perspective of this report, the implications that this rapid change can have on host-pest interactions (Logan *et al.* 2003), which are of greatest concern. Those interactions are exceedingly complex and difficult to forecast. It is known that the life cycles of many forest trees and pests are closely linked to one another and to their environment. It can, therefore, be anticipated that changes in the environment will alter this biological balance (Ayres and Lombardero 2000). Examples of such alterations have already been clearly evidenced by the unprecedented outbreaks of mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins) (Fig. 1) and *Dothistroma* needle blight (*Dothistroma septosporum* Dorog. M. Morelet) in British Columbia (BC), Canada. In both of these cases the role that climate played was well documented (Carroll *et al.* 2004, Woods *et al.* 2005) and the outbreaks align well with the scientific literature that forecasts increases in the severity and frequency of forest pests as one of the first observable signs of climate change (Pollard 1989, Graham *et al.* 1990, Joyce *et al.* 1990, Dale *et al.* 2001).

Previous outbreaks of MPB have been documented in BC (Safranyik and Wilson 2006) but the extent of the current epidemic, at over 14 million ha (Westfall and Ebata 2009), and the exhaustive nature, currently close to 50% of the entire

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provincial harvestable lodgepole pine (*Pinus contorta* Dougl. Ex. Loud var. *latifolia* Engelm) timber supply, dwarfs all records. In the case of Dothistroma, it is the severity of the current epidemic that sets this outbreak apart. In addition to the complete failure of 9% of pine plantations in the affected area of northwest BC, never before have mature native lodgepole pine trees been killed by Dothistroma needle blight (Woods *et al.* 2005). These coinciding outbreaks in BC underscore the uncertainty associated with predictions of future forest conditions under a changing climate.

It is important to consider that the changes in climate that have driven these alterations in forest pest behaviour in BC may be a response to the greenhouse gas (GHG) concentrations of the 1990s or earlier. A lag of several decades exists in the global climate system between the forcing of CO_2 concentration and temperature (Hansen *et al.* 2005). Combined GHG emissions rose by 20% between 1990 and 2004 with increased CO_2 emissions from the burning of fossil fuels being the dominant driver (IPCC 2007). In other words, we believe these examples of unprecedented pest outbreaks in BC that have been driven in part by climate change, may be just the beginning.

In this paper we present an assessment of the forest health implications of climate change for BC drawing on local experience and the growing body of literature on the subject for forests around the world (Ayres and Lombardero 2000, Aber *et al.* 2001, Dale *et al.* 2001, Hansen *et al.* 2001, Harvell *et al.* 2002, Logan *et al.* 2003, BCMFR 2006, Millar *et al.* 2007, Kirilenko and Sedjo 2007, Kliejunas *et al.* 2009). We have assumed that current climate trends will continue and have referred to Walker and Sydneysmith (2008), for regional (BC) climate change scenarios. Due to the uncertainty of predicting detailed insect, disease and decline impacts we believe it is only reasonable to project and discuss pest impacts for the near future—a maximum of 15 to 20 years. General principles and concepts associated with pests and climate change are outlined, and examples of forest health factors that are already having impacts are provided, as are anticipated changes to our current major forest pests. We also discuss implications of climate change to forest management in BC and what we feel are necessary management adaptations.

Forest Insects

A warming climate resulting in greater heat accumulation will increase the diversity of insects at higher latitudes and altitudes; thus, a greater diversity of insects will increase the feeding and predation stresses on tree hosts (Dale *et al.* 2001). Where droughts occur more frequently, stressed trees will provide a starting point for outbreaks. Similarly, extreme weather events that cause large-scale damage to forests will also serve as catalysts for increases in insect populations. In the following section we discuss current insect outbreaks in the forests of BC and forecast possible changes to those populations.

Bark beetles

Bark beetles are highly responsive to conditions created by climate change (Logan *et al.* 2003) and have already exceeded previously observed limits in Canada (Carroll *et al.* 2006).

The dynamics of bark beetle outbreaks are complex; numerous conditions and circumstances must coincide and a hierarchy of thresholds must be surpassed for an outbreak to occur (Raffa *et al.* 2008). Once a threshold is surpassed, however, prior controlling factors (such as natural enemies) exert little influence on population dynamics (Logan *et al.* 2003). Climate change appears to facilitate the breaching of outbreak thresholds.

While warmer winter temperatures have facilitated the outbreak of MPB in BC, it was the pre-existing landscape conditions of extensive areas of susceptible host trees that allowed it to reach its current magnitude and severity (Carroll *et al.* 2004, Safranyik and Wilson 2006). The three-fold increase in susceptible pine seen in the latter half of the 20th century provided ideal conditions for MPB to spread across BC and into Alberta (Carroll *et al.* 2006). In the coming decades it is anticipated that MPB will continue to spread, northward beyond its current range and to the elevational limits of pine species within the province, though perhaps not at an epidemic rate (Carroll *et al.* 2006). Many areas of mature and immature pine forests killed by MPB will again regenerate to lodgepole pine either naturally or through planting as it is often the most ecologically suited species. Depending on both the extent of climatic change and forest management decisions (e.g., fire suppression, forest health monitoring, harvesting, species selection and regeneration practices), a similar wide-scale MPB outbreak could occur within 70 years.

Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) outbreaks are often associated with weather-related events such as drought and windthrow (Furniss and Carolin 1977, McMullen 1984). To date in BC, outbreaks of this insect remain within historic levels of attack; however, climate change forecasts suggest that summer drought will be more common, as will winter windstorms. Should these forecasted trends continue, it is reasonable to anticipate that episodes of tree mortality caused by Douglas-fir beetle will increase in frequency. In addition to wind-throw and drought, Douglas-fir beetle populations also respond to trees stressed from prolonged periods of defoliation from western spruce budworm (*Choristoneura occidentalis* Freeman). Douglas-fir beetle populations could increase to epidemic levels in several areas of the province by exploiting warm dry conditions and the reduced resistance of budworm-defoliated trees. Evidence of such a trend is already occurring in the eastern Chilcotin region of BC (L. Rankin, Forest Entomologist, BC Ministry of Forests and Range, personal communication, Sept 29, 2009).

Spruce beetle (*Dendroctonus rufipennis* Kirby) is the most destructive pest of mature spruce forests in western North America. The beetle usually has a two-year life cycle but, at lower elevations and during warm summers, they can complete their development in one year (Furniss and Carolin 1977). A warming climate will increase heat accumulations, facilitating a conversion to a predominately one-year life cycle, which in turn will result in larger populations that can lead to more intensive outbreaks (Logan *et al.* 2003). Spruce beetle populations also respond readily to wind-throw events. When downed host trees are not removed, or otherwise treated, this material can produce high numbers of beetles capable of successfully attacking and killing standing spruce over extensive areas (Dyer and Taylor 1971). Increases in severe weather events will result in more blow-down, and hence a greater likelihood for spruce beetle outbreaks. Lower winter snow packs will increase drought stress, compounding the threats in areas already at high risk from beetles.

Spruce leader weevil

Spruce weevil (*Pissodes strobi* Peck) is the most damaging insect pest of young spruce in BC. Within high-hazard sites it significantly hinders Sitka spruce (*Picea sitchensis* [Bong.] Carr.) regeneration (Alfaro 1982). The success of weevil broods is strongly regulated by heat accumulation and weevil hazard zones have been delineated on this basis (McMullen 1976). As the climate warms, areas currently considered to have a low or moderate hazard will become increasingly more suitable for weevil broods. Simple modelling shows that an increase of only 1°C in the average temperature adequately warms the climate to convert many spruce weevil hazard zones to high hazard (Sieben and Spittlehouse 1991). The identification and propagation of weevil-resistant spruce genotypes will help mitigate the impacts of the weevil in regenerating Sitka spruce on the BC coast (King and Alfaro 2009) and in interior spruce (Engelmann [*Picea* engelmannii Parry] and white [*Picea* glauca (Moench) Voss], plantations (King *et al.* 1997).

Defoliators

Outbreaks of defoliating insects can arise over extensive areas given favourable weather conditions (Williams and Liebhold 1995). Climate change may result in more frequent favourable weather and therefore more frequent defoliator outbreaks (Flemming and Volney 1995).

Western spruce budworm (*Choristoneura occidentalis* Freeman) has a long history of outbreaks in dry Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco. var. *menziesii*)-dominated forests of BC (Campbell *et al.* 2006). Current budworm outbreaks in the province are distinguished by their expansion into higher elevations (Maclauchlan *et al.* 2006). The most recent outbreak period, 1995 to 2009, has seen the budworm move north into Douglas-fir stands that had no prior records of infestation. The climate has become more conducive to budworm, and stand structure is also at a higher hazard/susceptibility than in the past. As the climate warms, budworm may continue to expand in range toward the limit of its primary host, Douglas-fir.

Another key factor in budworm population dynamics is synchrony with tree development (Logan *et al.* 2003). A warming climate may allow for a more synchronized emergence with host phenology in more northern and higher-elevation sites where suitable hosts are available. Western spruce budworm may become less successful at warmer, lower elevations due to asynchrony with tree development.

Within the past 100 years there have been seven recorded outbreaks of western hemlock looper (*Lambdina fiscellaria lugubrosa* [Hulst]) on the coast and eight in the interior that have involved substantial hemlock mortality and salvage harvesting (Turnquist 1991). Entire stands of western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) can be killed following only one year of severe defoliation and once dead, western hemlock becomes unmerchantable within a few years. Outbreaks of this defoliator have been forecast to occur more frequently and to be more widespread on the coast of BC as a result of a warming climate (McCloskey *et al.* 2009). Most climate change models predict warmer and drier summers for coastal BC—the very conditions that seem to have historically triggered outbreaks of this looper (McCloskey *et al.* 2009).

Forest Pathogens

Of the two principle components of climate, temperature and precipitation, insects are most directly affected by the former, pathogens the latter. The ability to accurately predict changes in fungal pathogen populations and behaviour is less than that for insects because of the difficulty in predicting changes in precipitation patterns (IPCC 2007). Most climate models produce outputs on seasonal or monthly time scales, but organisms that dominate ecosystem responses to climate change can be sensitive to precipitation patterns on shorter scales (Weltzin *et al.* 2003).

Foliar diseases

Projections of climate change impacts on foliar disease behaviour are challenging and highly uncertain because of their direct tie to precipitation. Increased incidence of drought could decrease the severity of some foliar diseases (Kliejunas *et al.* 2009). A human influence on twentieth-century precipitation trends has recently been detected, however, suggesting an increase in precipitation poleward of 50°N (Zhang *et al.* 2007). There is also a general consensus among climate change predictions that daily minimum temperatures are expected to increase more than daily maximums (Harvell *et al.* 2002). Night-time minimum temperatures in most regions of BC are warmer on average than they were a century ago, particularly in spring and summer (BCME 2002). Increases in precipitation and in overnight minimum temperatures and the potential for greater over-winter survival of foliar fungi due to warmer winters could all favour the development and spread of foliar diseases (Coakley *et al.* 1999).

Foliar diseases in native forests generally have minor impacts due to high levels of host resistance (Harrington and Wingfield 1998); however, the example of *Dothistroma* needle blight in northwest BC suggests this historical trend may no longer hold (Fig. 2). The *Dothistroma* epidemic has coincided with a marked increase in summer precipitation and an increase in the frequency of warm, wet days (Woods *et al.* 2005). Although the specific environmental requirements of other foliar diseases are not as well known, it is reasonable to assume that conditions that have favoured *Dothistroma* needle blight would favour many similar foliar diseases.

Stem rusts

Pine stem rusts are one of the most damaging groups of forest pathogens of young pine in BC (Lowe and Ziller 1977, Woods *et al.* 2000). The life cycles of all native tree rust species are strongly influenced by environmental conditions, particularly by precipitation during the growing season (Ziller 1974). When specific optimal environmental conditions are met, peaks of rust infection or "wave years" occur, historically once every decade (Peterson 1971). Wave years for western gall rust (*Endocronartium harknessii* [J.P. Moore] Y. Hiratsuka) require cool, moist conditions in late spring (van der Kamp 1988). Wave years for other stem rusts, including white pine blister rust (WPBR; *Cronartium ribicola* J.C. Fisch), comandra (*Cronartium comandrae* Peck) and stalactiform blister rust (*Cronartium coleosporioides* Arthur), require cool, moist conditions in mid- to late-summer (Mielke *et al.* 1968, Hunt 2004). The frequency of wave years appears to have increased over the past decade throughout central BC coinciding with a trend towards increased precipitation and higher overnight minimum temperatures (BCME 2002).

Changes in climatic conditions that result in warmer and wetter late springs and summers will likely increase the risk of damage in most areas that already suffer losses to rusts. In some areas of the province that currently suffer significant rust damage, the climate may become too dry for rust fungi in the future.

Root diseases

There is as yet no conclusive study linking climate change to increased root disease activity in BC. Elsewhere in the world such studies do exist and were some of the first to suggest that climate change was responsible for altered forest pathogen behaviour (Brasier and Scott 1994, Brasier 1996). These studies found that climate change was a probable cause of drought stress, which predisposed host trees to a root disease. Climate models for BC suggest that current and future climates will place large geographical areas of the southern interior under greater drought stress and therefore at higher risk to root disease. *Armillaria* (*Armillaria ostoyae* [Romagnesi] Herink) root disease is prevalent throughout a large proportion of southern BC forests, on a wide host range, causing significant growth loss and moderate rates of mortality (Morrison *et al.* 2000). If climate change results in large areas of the southern interior of BC becoming dryer, it is likely that the impacts of *Armillaria* root disease will increase significantly as has been forecast for the drier north-western parts of the US (Klopfenstein *et al.* 2009) and Ontario (Boland *et al.* 2004). The same general pattern of increased root disease impacts being associated with increased host tree stress will likely hold for the other major root diseases such as, *Phellinus* (*Phellinus weirii* [Murrill] R.L Gilbertson), *Tomentosus* (*Inonotus tomentosus* [Fr.:Fr.] S. Teng) and *Annosus* (*Heterobasidion annosum* [Fr.:Fr.] Bref.).

Although it is expected that timber losses to root disease will increase under climate change, the expansion of root pathogens into new ranges will perhaps be slower than that of rusts and foliar diseases. The latter two groups spread primarily by airborne spores, capable of considerable travel, while root diseases tend to spread through root contacts among host trees.

Dwarf mistletoe

Dwarf mistletoe infections weaken trees and may predispose them to further damage from other biotic agents. Climate change will increase the likelihood of drought and warmer winter temperatures, affecting tree resilience, mistletoe biology and allowing for geographic and elevational range expansion. An increase in lodgepole pine dwarf mistletoe (*Arceuthobium americanum* Nutt. Ex Engelmann) impacts, has been forecast for Ontario as a result of climate change (Boland *et al.* 2004). The same logic holds in BC, although the MPB epidemic has substantially reduced the quantity of mature hosts of dwarf mistletoe, possibly reducing the impact of this disease for the time period covered in this document. Decreased snow loads and warmer winter temperatures could facilitate the migration of Douglas-fir mistletoe (*Arceuthobium douglasii* Engelmann) both further north and towards the coast and hemlock dwarf mistletoe (*Arceuthobium tsugense* [Rosendahl] Jones) to inland areas of BC.

Alien invasive pests

Alien invasive pests pose serious threats to BC forests as they do to forests throughout the world (Harvell *et al.* 2002). While climate change does not directly affect the rate of introduction of new pests, it can provide host trees that are stressed or provide environmental conditions that are more amenable for pest establishment. Through increased international trade and movement of goods the likelihood of accidental introductions of invasive species remains high (McNeely 2000). The introduction of alien invasive forest insects and disease can irrevocably alter forest biodiversity. To date, a cold winter climate that is not favourable to many exotic pests (Harvell *et al.* 2002) has been our best natural defence in much of BC.

White pine blister rust is an alien invasive pathogen that was introduced into the forests of North America in the early 20th century (Hunt 2009). It has devastated western white pine (*Pinus monticola* Douglas ex D. Donn) and other five-needle pines including whitebark pine (*Pinus albicaulis* Engelm.) in BC. Although the introduction of WPBR was not related to climate change, it serves as an illustration of how an alien pest attacking a tree species with little or no host resistance can have devastating consequences. This example emphasizes the negative implications associated with host trees being exposed to novel pests as has been forecast under climate change (Harvell *et al.* 2002). Alien invasive pests in tandem with a changing climate will present unique challenges to forest ecosystems.

Pest Complexes

Individually, many insects and diseases have only a minor impact on tree health. When multiple pests interact, however, the health of stands can be compromised. As the climate continues to change and trees become more stressed, relatively innocuous insects and diseases acting together could become significant (Ayers and Lombardero 2000).

The emergence of pest complexes in young stands presents a particularly serious concern. The current MPB epidemic has intensified the pressure placed on regenerating forests to contribute to mid-term timber supplies (BCMFR 2007). Any further losses in these young stands to insects and disease are magnified because we have lost the timber supply buffer formerly provided by the mature lodgepole pine stands (Fig. 3).

In young lodgepole pine stands, it is common to encounter western gall rust, stalactiform and comandra blister rusts, *Atropellis* canker (*Atropellis piniphila* [Weir] Lohman & Cash), terminal weevil (*Pissodes terminalis* Hopping) and more recently, MPB and pine engraver (*Ips pini* Say) , all coexisting in one stand.

Species selection, silviculture treatments and pest management are all critical to the success of future forests and the interaction of these factors must be closely monitored. Manipulation of stand density influences pest dynamics and, in some cases, makes trees and stands more susceptible to attack by insects and diseases. Careful consideration and planning are required to conduct stand-tending activities that will reduce susceptibilities. The interaction of the environment, treatment, host and pests must be monitored and adaptive management applied.

PHOTO: L. MACLAUCHLAN

Fig. 1. Lodgepole pine-dominated landscape in central BC transformed by current mountain pine beetle epidemic.

PHOTOS: A. WOODS

Fig. 2. Mature (60-year-old) lodgepole pine trees (left) and a young pine plantation (right), both examples of Dothistroma needle blight-caused mortality in NW BC.

Photo: A. Woods

Fig. 3. The current mountain pine beetle epidemic has intensified the pressure placed on regenerating forests to contribute to mid-term timber supplies.

Decline Syndromes

Tree mortality is often not attributable to any one agent, but is the result of a number of diseases and secondary insects acting in combination. These occurrences have been termed "decline syndromes" (Manion 1981). Declines are often geographically widespread and are typically associated with moisture stress. Physiologically stressed trees are more likely to experience growth impacts and the slow decline of tree health (Ayres and Lombardero 2000). The interaction and ultimate impacts of declines will increase in importance as climate change puts additional stresses on forests. Occurrences of decline syndromes have increased in many of the world's forests, including those of western North America such as western boreal aspen forests (Hogg *et al.* 2008), coastal yellow-cedar (*Callitropsis nootkatensis* [D. Don] Florin) forests (Hennon *et al.* 2005, Schaberg *et al.* 2008) and BC interior birch stands (*Betula papyrifera* Marsh.) (Westfall and Ebata 2009).

Drought-related declines

In 1998, and again in 2003, the southern interior of BC experienced a significant drought, which contributed to over 10 000 ha of drought-related tree mortality. Some of this mortality was a direct result of water stress on sites that were drought-prone, such as those having shallow soils and areas of transitional grassland. Much of the mortality was a result of secondary insect attack on stressed trees (e.g. *Ips*, *Pityogenes* and others) and on increased root disease activity (A. Stock, Forest Entomologist, BC Ministry of Forests and Range, personal communication, 2008).

Photo: L. MacLauchlan

Fig. 4. The world-renowned Illingworth lodgepole pine provenance trial provides both an indication of which families of lodgepole pine might be more productive under climate change as well as a stark reminder of the influence of insects and disease.

High-elevation forests are less tolerant of drought and fire, and both phenomena could increase in frequency and severity in the coming years (Flannigan *et al.* 2000). The same forests will also become increasingly vulnerable to opportunistic pests as dramatic climate fluctuations increase in frequency. Mortality of subalpine fir (*Abies lasiocarpa* [Hooker] Nutall) in permanent monitoring plots located throughout the southern interior of BC has increased since 1998 (Joy and Maclaughlin 2001). The mortality is being caused by the western balsam bark beetle (*Dryocoetes confusus* Swaine), and by a typically innocuous *Pissodes* weevil that is now acting like a primary bark beetle.

Over the past decade mortality and dieback of western redcedar (*Thuja plicata* Donn ex D. Don) has been observed within the driest areas on the coast of BC. This was especially evident following the summer of 1998 and was repeated throughout the early 2000s (D. Heppner, Ministry of Forests and Range, personal communication, 2008). Periods of drought over the past decade and during the summer of 2007 in particular, have resulted in stressed western redcedar appearing in large numbers throughout the southern interior of BC.

Yellow-cedar decline

Yellow-cedar decline has been identified in south-eastern Alaska for several decades (Hennon and Shaw 1994) but, until recently, its occurrence and impact was poorly documented in BC. Recent assessments along the coast indicate that over 40 000 ha of decline have been mapped in the province and this may affect the future range of this species (Hennon *et al.* 2005). Yellow-cedar decline is considered to be a result of long-term climate change (Schaberg *et al.* 2008). Declining snow depths at lower elevations of the species range has led to increased susceptibility of fine roots to late-season frost events (Hennon and Shaw 1994). Under climate change it is likely that yellow-cedar will continue to decline as snow packs recede earlier in the spring due to lower annual snowfall.

Birch decline

The decline of paper birch (*Betula papyrifera* Marsh.) has become very prominent throughout much of southern BC. The phenomenon appears to be a result of several factors working in concert that prevent normal tree growth, limit defensive processes, and cause top-kill and tree death. An insect–pathogen complex of bronze birch borer (*Agrilus anxius* (Bury), several birch leaf miner species, and pathogens are suspected but changing environmental conditions may be the underlying cause. Summer drought stress, temperature variability and freeze–thaw events have likely reduced tree vigour and growth, and increased the incidence of pests. Several studies suggest that region-wide birch dieback is caused by extreme freezing and/or moisture fluctuations, which permanently damage functional living tree tissues (Clark and Barter 1958, Braathe 1996, Cox and Malcolm 1997). The frequency of such climate events is expected to increase in the future. This may push paper birch beyond its adaptive limits, leading to large-scale dieback throughout its current range.

Implications For Forest Management

The changes in forest pest occurrences that have already taken place in BC are challenging both management and operational capacity. These challenges will increase. At the same time, the more universal impacts of climate change on societies will influence the value-ranking of multiple forest resources. Management of the provincial forest landbase for water resources, biofuels or carbon sequestration may become more important than the current emphasis on timber. The choices could be as fundamental as that of food, fuel or fibre (http://www.for.gov.bc.ca/mof/Climate_Change/Roberts_BCPremiersSymposium.pdf). Regardless of the future use for forest resources, effective management of forest insects and diseases will be crucial to all aspects of forest management, from research and policy formulation through to planning and operations.

Forest management needs to respond and adapt to accommodate the diverse and innovative practices that will be required to manage forests into the future. Within this process, managers must anticipate events outside the range of conditions that have occurred in recent history (Millar *et al.* 2007). This is probably one of the most challenging aspects of forestry under the new reality of climate change, since so much of our understanding of forest ecology, growth and dynamics is based on past experiences (Puettmann *et al.* 2009). Forest management, is entering an era of unprecedented uncertainty as a result of climate change (Kirilenko and Sedjo 2007). An uncertain future can be best addressed with approaches that offer institutional flexibility, and that include risk-taking, an ability to reassess conditions frequently, and a facility to change direction as conditions require (Hobbs *et al.* 2006). While proactive management of forest ecosystems for resilience to insect and disease impacts should be a primary focus of forest management, the need for a greater range of direct control options remains.

In the following section we tie the current and predicted changes in forest insect and disease behaviour under climate change to several key aspects of forest management that we believe will be significantly impacted. Our coverage of forest management impacts addresses only a fraction of the full scope. We have focussed on the areas where we feel forest health agents have the greatest influence.

Timber supply forecasting

Timber supply will be reduced by the impacts of insects and disease under the influence of a changing climate because of declining tree health and increased mortality. Already, the mountain pine beetle epidemic has been forecast to reduce mid-term timber supplies by over 70% in some areas of BC (BCMFR 2007). The combination of direct and indirect effects of climate change on forest health will continue to fundamentally affect the ability to make accurate timber supply projections over the long term. Large or frequent disturbances present a challenge to forecasting a sustainable timber supply, particularly when the extent and severity of the events are uncertain, unprecedented and subject to ongoing changes in the climate. Although, the MPB epidemic represents a current extreme example, it is possible that the combined impacts of multiple pests under the influence of climate change could approach a similar magnitude of impact on the remaining timber resource.

Timber supply is based in part on predictions of managed stand productivity and on the current assumptions associated with juvenile stands. These assumptions are based on the premise that young trees grow according to predictable growth and yield models. These models were largely developed assuming a stable environment. We already have evidence of changing climatic conditions in BC (BCME 2002) and clear examples of the effects of those changes on forest insects and disease (Carroll *et al.* 2004, Woods *et al.* 2005). These changes in insect- and disease-related impacts on forests are making accurate timber supply projections much more challenging.

While historical parameters have been used in timber supply projections, such deterministic information cannot form an adequate basis for timber supply modeling given climate change (Millar *et al.* 2007). The most up-to-date information on forest pest occurrences and damage must be incorporated into timber supply analyses and harvest level decisions, and this requires improvements in both stand- and forest-level monitoring practices.

Monitoring

Adequate monitoring in terms of both scale and frequency is essential for managing forests in a way that achieves a sustainable flow of multiple products and values. While surveys and reports serve well to detect and quantify the severity and extent of disturbances, monitoring focuses on the long-term, widespread, unexpected and sometimes subtle changes that provide early indication of changing stand health. Although aerial overview surveys can capture insect and disease occurrences at medium to large scales, many forest health interventions are best applied at the incipient stage. Monitoring for insect and disease occurrences at a finer scale than current standard aerial overview surveys is essential. Monitoring programs need to be coordinated across spatial scales, providing long-term records that can be used effectively in landscape management. An effective monitoring program adds to our understanding of how pests affect forests and how climate change is influencing ecosystem dynamics and managed stand productivity.

Modeling

Climate models coupled with environmental envelopes such as those developed by Hamann and Wang (2006) provide a powerful tool to forecast the potential range of changes across a landscape. The next step is to couple those changing environmental envelopes with the ecology of forest insects and disease. Such models exist for climate, forests and forest insects, and synthesizing and analyzing these models may be the best way to evaluate events that might occur in the future (Logan *et al*. 2003). Pest modeling can provide qualitative insights on the magnitude and direction of events but much uncertainty remains. Climate models can provide predictions of the effects of a changing climate on trees and pests; however, it is acknowledged that models do not yet take into account the potential adaptive responses of pests to climate change (Desprez-Loustau *et al*. 2007). This is a largely unexplored field that needs further investigation.

Risk rating

Hazard and risk-rating systems are integral components of forest health plans and should be in place, and applied, in advance of insect and disease outbreaks. As these systems have proven to be useful when attempting to forecast future pest impacts due to climate change, they should be a priority for forest health research and development. However, it may be that for many insects and pathogens, rating systems either require refinement to account for climate change or have not been developed. Relating historical occurrence with biogeoclimatic zone variants can be helpful in the interim.

Assisted migration and genetic diversity

Increased species and genetic diversity in combination with facilitated migration is one of the most effective, efficient, and durable methods to maintain healthy plantations in the face of climate change (Millar *et al.* 2007, O'Neill *et al.* 2008). Planting species and populations (seedlots) that are adapted to future climates preserves the host-pest balance that has been created over millennia. Provenance tests reveal that the incidence of pest attack increases sharply when populations are planted in climates that differ significantly from their origin (O'Neill *et al.* 2002). The facilitated migration of tree species provides an opportunity to increase stand resiliency and reduce susceptibility to pests. Increasing the number of species and seedlots of a species on the landscape—each having a slightly different climatic/adaptive optimum—provides a buffer against increased pest risk (Ledig and Kitzmiller 1992, Millar *et al.* 2007). Most forest pests are species-specific so the simple act of increasing the number of species directly reduces the risks of a plantation, and management goals, from being compromised by any one pest species. Although such adaptation options may improve the resiliency of forest plantations, the vast majority of forests will have to adapt to changing conditions without human intervention (Spittlehouse and Stewart 2003).

Climate change will challenge the ability of forest managers to redistribute seedlots to projected climates where they will be best adapted in the future, while simultaneously maintaining projected levels of genetic gain in growth (i.e., genetic worth of the seedlots). With elevated activities of pests and diseases induced by climate change, it is most appropriate to increase the focus on resistance traits, as well as growth potential (Fig. 4).

Gene conservation and tree breeding

Gene conservation will be critical as climate change unfolds, both for maintaining and enhancing the resilience of forests, and for the hope of improving forest level resistance to pests. To this end, conservation of seed sources both *in-* and *ex-situ* for all tree species is essential (Yanchuk 2001). Even with those efforts, given the magnitude of projected climate change, it is conceivable that over the next century threatened tree species, such as whitebark pine, could become locally extirpated over much of their current range. Direct interventions to preserve species may be required (Spittlehouse and Stewart 2003), but such efforts will have to be weighed against the expectation of success and on other demands on limited resources.

While successful resistance breeding programs in trees are not common, examples exist in BC that include programs for spruce leader weevil (King *et al.* 1997) and WPBR (Hunt 2004). These successes have required decades of development. With climate change, factors affecting host-pest interactions are changing rapidly, generally in favour of pests (Logan *et al.* 2003). This rate of change may exceed the current capacity of breeding programs to keep pace. The unprecedented level of uncertainty of climate trends, host conditions and changes in pest dynamics, signals a need to investigate resistance mechanisms that will provide a general pest tolerance or resistance in addition to species- specific resistance (A. Yanchuk, Research Leader, Forest Genetics, BC Ministry of Forests and Range, personal communication, 2009).

Conclusions

The management of forest lands in BC has already become more challenging as a result of climate change. The MPB and *Dothistroma* needle blight outbreaks have led to fundamental changes to forest management in the province. *Dothistroma* has resulted in lodgepole pine no longer being considered a preferred tree species for management in the epidemic area and instead plantations of lodgepole pine in northwest BC are considered as uncertain liabilities. The far more extensive MPB epidemic has driven change in silvicultural system choices and has dramatically reduced mid-term timber supply in the interior of BC (BCMFR 2007), directly impacting the stability of several timber dependent communities. Even more fundamental to the global crisis of climate change, the MPB epidemic has contributed to the shift of BC's interior forests from being net carbon sinks to net sources of carbon (Kurz *et al.* 2008) and so represents an example of a positive feedback loop (Field *et al.* 2007). The worst case scenarios of global warming as outlined by the IPCC (2007) have since been shown to be conservative due to the omission of such positive feedback loops (Field *et al.* 2007). By extension this revelation could conceivably result in a shortened time frame and increased severity of our forecast changes to insect and disease behaviour.

We believe the current system of forest management, based on predictable ecosystem responses, is not consistent with the rapidly changing ecology that has been forecast. The need for change is already evident. Forest management must become more flexible with reversible, incremental steps that favour ongoing learning and the capacity to change direction as situations change (Millar *et al.* 2007). The need for forest health management to be more directly aligned and fully integrated with forest management is essential under climate change. Forest health management will rely on monitoring, planning and a proactive approach, based on risk analysis. The risks associated with trying to maintain the status quo far exceed those of implementing changes that provide for a broader spectrum of future forest conditions.

The task for the next decade is to understand better how climate affects biotic and abiotic disturbances and how forests respond to them. Improved monitoring programs and analytic tools are needed to develop this understanding. Ultimately, this knowledge should lead to better ways to predict and cope with disturbance-induced changes in forests. We must not think of climate change impacts in our forest as solely a timber supply problem, when it is an overall forest problem affecting all values, present and future. The entire natural capital base, therefore, should be managed with a stewardship purpose consistent with the public interest in our forest asset.

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