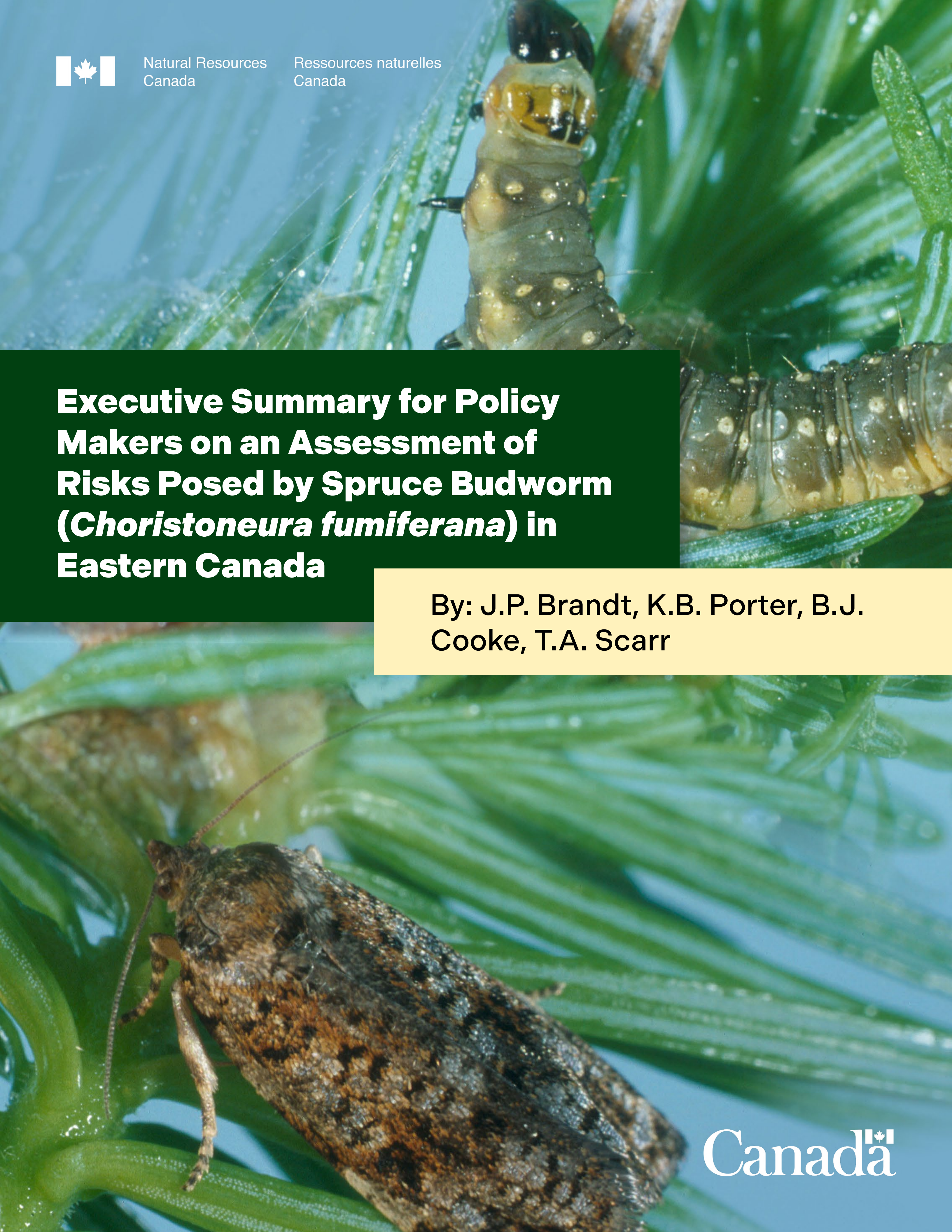

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By: J.P. Brandt, K.B. Porter, B.J. Cooke, T.A. Scarr

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Introduction

This executive summary for policymakers and the companion full report[1], titled "*An assessment of risks posed by spruce budworm* (*Choristoneura fumiferana*) *in eastern Canada*" is intended to be a reference for forest pest managers in developing contemporary strategies for spruce budworm (hereafter referred to as SBW), provide background for decision makers and policy developers, and help researchers identify opportunities for relevant scientific studies.

Spruce budworm is a conifer-feeding insect native to boreal and hemiboreal forests of North America east of the Rocky Mountains. Periodic outbreaks in Canada cause significant defoliation in spruce-fir forests resulting in damage ranging from growth loss to tree mortality. Such impacts are natural disturbances in northern forests but can cause significant economic loss of forest resources, negatively affecting the forest industry and forest-dependent communities as well as altering non-consumptive forest values such as recreation, wildlife, carbon sequestration, and cultural identity. Since 2006, eastern Canada has been experiencing a SBW outbreak. The previous outbreak collapsed in the 1990s (additional details on the current and past outbreaks are outlined in the full report).

Susceptibility and vulnerability[2] vary among host tree species and among forest stands. Both balsam fir (*Abies balsamea* (L.) Mill.) and white spruce (*Picea glauca* (Moench) Voss) are about equally susceptible to SBW. Red spruce (*Picea rubens* Sarg.) and black spruce (*Picea mariana* (Mill.) are less susceptible. Such differences in susceptibility are best explained by synchronization of tree-insect phenology. The water and nitrogen content of balsam fir, along with its needle softness, are at their maximum at the time of budburst, which is closely matched to the emergence of overwintering second-instar SBW (L2) larvae. White spruce is less synchronized with SBW, flushing about 4 days later than balsam fir, and its nitrogen content is lower than balsam fir. Red and black spruce are less suitable because budburst occurs about 13 days later than balsam fir, meaning that there is no new succulent foliage for SBW larvae to feed on when they emerge on these hosts, which decreases larval survival. Balsam fir is also more vulnerable than any of the spruce because it carries a lower complement of foliage, and SBW larvae will feed on both new and older needles. Thus, the higher the proportion of balsam fir in a particular stand, the greater the impacts of SBW.

The pronounced nature and impacts of SBW outbreaks have made the insect the subject of significant research and management for more than 100 years. The pest's life cycle, history of outbreaks, and management interventions are well documented. This knowledge base, however, is largely technical in nature and specific in context. The full report is the result of expert opinion supported by the literature and synthesizes decades of research on SBW, including many studies undertaken during the last ten years. It builds on these earlier works and assesses the current risks of SBW outbreaks in eastern Canada.

[1] Citation for full report: Brandt, J.P.; Porter, K.B.; Cooke, B.J.; Scarr, T.A., editors. 2025. An assessment of risks posed by spruce budworm (*Choristoneura fumiferana*) in eastern Canada. Natural Resources Canada, Canadian Forest Service. Ottawa, Ontario. Information Report. 92 p.

[2] Susceptibility of a host or forest is defined as the probability that the host or forest will be attacked by SBW; vulnerability is the probability that damage, such as reduction in tree growth and tree mortality, will result from SBW defoliation (Blum and MacLean 1985).

SBW Outbreaks and Management

Historical evidence from dendroecological data and annual aerial detection surveys indicates SBW outbreaks recur every 30 to 40 years in Canada east of the Rocky Mountains. Outbreaks can persist more than 10 years in any one area and cause tree mortality, especially in more vulnerable balsam fir. Three major outbreaks occurred in the 20th century. The last outbreak reached its peak in the 1970s, with moderate-to-severe defoliation affecting more than 50 million hectares of forest.

Although the aerial application of insecticides has been one of the primary methods of managing SBW outbreaks since the 1950s, forestry jurisdictions in Canada have been implementing an integrated pest management (IPM) framework for several decades. Under IPM, all options available to forest and pest managers are considered carefully when trying to minimize the negative impacts of a SBW outbreak. One direct method of management includes applying an insecticide under a reactive foliage protection strategy (FPS), targeting previously defoliated, high-value stands to keep trees alive until the outbreak subsides or trees can be harvested. Repeated annual applications to stands may occur. At present, the most widely used insecticide in Canada is the bacterium, *Bacillus thuringiensis* (*Bt*) with more limited recent use of insect growth regulators. There has always been an interest in more proactive management approaches, such as an early intervention strategy (EIS). This approach aims at preventing damage by altering budworm population behaviour. Earlier attempts at an EIS have been tried but with limited area-wide efficacy. The most recent EIS incorporates intensive monitoring of low-density populations nearest currently infested areas to detect rising populations before damage becomes evident. These areas are targeted for the application of insecticides to prevent populations from exceeding the irruption threshold that leads to outbreaks. Experimental trials since 2014 have proved promising in maintaining low populations of SBW in northern New Brunswick despite a larger regional outbreak in nearby Quebec. However, beyond 2026 (when the current experiment ends), and in broader areas where SBW outbreaks occur, the applicability of the EIS is untested, and there are likely key questions that will remain unanswered at the end of the experiment. Silvicultural approaches afford another set of options for forest managers when dealing with a SBW outbreak. The latter include (i) pre-emptive harvesting and accelerated harvesting of host stands expected to be defoliated and otherwise damaged by SBW, and (ii) salvage logging, which is the harvesting of trees that are dead, dying, or deteriorating before the fibre of the affected trees loses its economic value. Another option under IPM includes no action, where the outbreak is left to run its course without interventions. The choice of any management option depends largely on what the specific forest management objectives are for any given stand or area.

Risk Analysis

Working together under the Canadian Council of Forest Ministers, federal, provincial and territorial governments have promoted risk analysis as a proactive approach to achieve harmonized, evidence-based forest pest management policies and practices. Risk analysis is a multidisciplinary approach that informs decisions in the context of threats at all relevant scales. It is a strategic tool that identifies evidence to inform policy and operational decisions.

Risk is the product of likelihood of occurrence of an event and expected consequences if the event occurs. Risk analysis includes assessment, response, and communication. Risk assessment and response are knowledge-based facets of the analysis, addressing the questions "what do we know?", "what does it mean?" and "what should we do?". Risk communication conveys information upwards within management agencies to decision makers, downwards within the organization to those implementing the response, and outwards to partners, collaborators, stakeholders, and Indigenous peoples. This executive summary for policymakers summarizes, and the full report describes, a risk assessment for SBW intended to integrate our latest understanding of SBW biology, ecology, and management; qualify our confidence in that understanding; and identify research needs to reduce uncertainty. Details, including references, are provided in the full report.

The trigger for this assessment is the persistence and expansion of the current SBW outbreak that first appeared in Quebec in 2006. As of 2021, the outbreak remained centred in Quebec, but populations are increasing in Ontario (Fig. 1). Both latter jurisdictions use a conventional foliage protection strategy in which high-density budworm populations in damaged, high-value stands are suppressed by aerial application of insecticides. Quebec has sprayed every year since 2009, treating 741,000 ha of forest in 2021. Ontario treated more than 53,914 ha in 2021. Ontario's spray programs in 2020 and 2021 were their first since 1991. SBW populations in Atlantic Canada have been kept below damaging levels since 2014 through the experimental implementation of a novel EIS which closely monitors forests in northern New Brunswick and responds quickly to increasing threat. This same approach is being attempted in western Newfoundland, where SBW populations are augmented periodically by large influxes of immigrating moths from Quebec. The imminent threat of further expansion of the area of infestation and the possibility of novel strategies for management based on advances in knowledge of SBW ecology makes this risk assessment a timely introduction to a more comprehensive approach to evaluating risk in northern conifer forests.

A workshop of invited research scientists and experts from the forest pest management community was convened in four 3-hour sessions in August 2021. Affirmative statements (AS) pertinent to the risk of SBW outbreaks were presented to drive a discussion of scientific evidence and expert opinion on the state of relevant knowledge. For each statement, associated uncertainties and information required to reduce uncertainty (i.e., knowledge gaps) were identified. Following the workshop, writing teams prepared sections of the full risk assessment report using notes from the workshop supplemented with additional information and expert knowledge to fill gaps and complete a synthesis of their assigned topic. This assessment also includes sections on current management responses to outbreaks. These are included because assessing risk, efficacy, and uncertainty around existing management responses reflects the iterative nature of risk assessment and analysis. Table 1 summarizes the key evidence related to each AS discussed and reviewed as part of the risk assessment process.

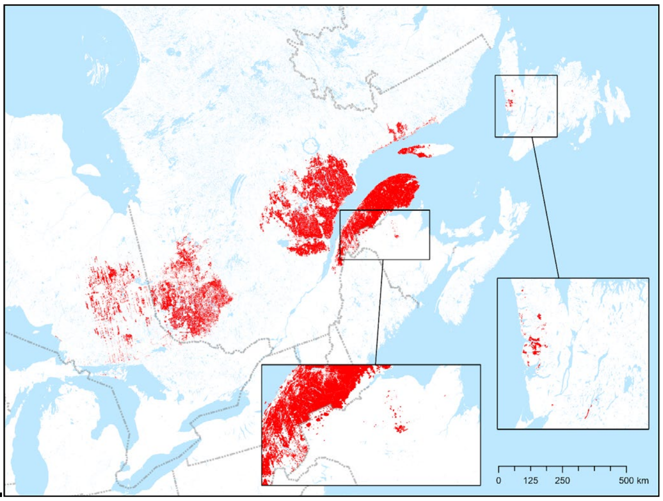

Figure 1. Extent of spruce budworm defoliation in eastern Canada in 2021.

Table 1. Key evidential points related to affirmative statements discussed and reviewed as part of the risk assessment process related to SBW outbreaks.

Affirmative statement:	**AS 1: SBW outbreaks are periodic in occurrence and the mechanisms of population irruption are well understood**	**AS 2: SBW population irruptions are preventable**
Authorities of work on AS:	B.J. Cooke, J. Régnière, J.-N. Candau	B.J. Cooke, J. Régnière, J.-N. Candau
Key points:	▪ Extensive periodic outbreaks observed across several centuries within the dendroecological record, and over several millennia within the paleoecological record. ▪ There is significant spatial variation in outbreak behavior, some of which appears to be attributable to spatial variations in climate and forest structure, although much of the variation in periodicity, intensity, and duration remains unexplained. ▪ The phenomenon of epicenter formation is not a mere historical anomaly but was a prominent feature in the early development of the current outbreak cycle in northern Quebec. The early phase of population cycle initiation is marked by a period of positive density-dependent recruitment caused by improved mating success with rising density through time. ▪ Although severe budworm outbreaks do result in tree mortality, in the bulk of the insect's range, the outbreak cycle terminates with only growth loss and minimal tree mortality. ▪ A wide range of natural enemies induce periodic population cycling. SBW-natural enemy interactions are not simple, however, and are likely mediated by environmental factors, including forest composition and its influence on not just the community of natural enemies affecting budworm but also their own predators and their own suite of alternate hosts.	▪ The central thesis of the early intervention approach to population management is that there is an unstable low-density population irruption threshold below which growing populations may be driven by insecticide application. Recent data suggest that the irruption threshold exists, is unstable, and that it occurs at roughly 3 to 5 L4 larvae per branch or a comparable population level of 7 L2 per branch. ▪ If the irruption threshold drifts because of forest growth through time, then the question of prevention becomes challenging. Prevention may be possible in the short run, but this result may eventually become infeasible as the threshold is exceeded. Similarly, if there is a propensity for cycling induced by natural enemy interactions, then preventability may lessen as natural enemies become increasingly scarce, resulting in an insurmountable upward pressure on SBW population growth. ▪ Emergence of the current SBW outbreak in Quebec has provided new data on the role of natural enemies in releasing populations from endemic levels. So far, there is no evidence of an impoverished natural enemy community, despite there having been two decades of low budworm densities between the collapse of the last outbreak and the initiation of the current one in 2006. The EIS in New Brunswick has been successful in limiting population growth across the province, and there is no evidence of natural enemies dropping out and thereby releasing their regulating effect on SBW populations. ▪ Preventability of SBW population irruption is a matter of scale and economics. An irruption that is preventable at the level of the tree, stand or focal epicenter, may not be preventable at the level of the landscape, because there may be economic, regulatory, or logistical barriers to upscaling an intervention program. Prevention requires continuous early detection, and the logistics and economics of early detection can be a barrier to pursuing the EIS. What is feasible for a small, highly timber-dependent province may be practically and economically infeasible for larger provinces. ▪ Localized population irruptions at the level of the tree, stand or watershed may be indefinitely preventable. Larger-scale, region-wide outbreaks may be preventable for a certain amount of time, but it is uncertain whether the approach can be applied long-term. At the largest scales, cycling behavior may eclipse all locally irruptive behaviour.
Affirmative Statement:	**AS 3: Long-distance dispersal of SBW moths is a major factor in outbreaks**	**AS 4: Climate change is altering the distribution, scale, and intensity of SBW outbreaks in the forests of eastern Canada**
Authorities of work on AS:	B.J. Cooke, J. Régnière, J.-N. Candau	A.D. Roe, D.S. Pureswaran, J.J. Bowden, J. Régnière, E.R.D. Moise, V. Martel
Key points:	▪ SBW dispersal occurs at a wide range of spatial scales, from meters to hundreds of kilometers. ▪ Understanding of the environmental factors affecting long-range dispersal has improved considerably, with canopy observations of take-off flights and radar observations of atmospheric transport. ▪ Mechanistic models of moth dispersal indicate that much of the dispersal of SBW moths is wind-driven and therefore that wind direction and wind speed play a critical role in determining moth flight paths. ▪ There appear to be two major ways in which dispersal can contribute to cycling and spread. First, immigration events can trigger irruptive growth and spread. Whether this happens depends on the receiving population already being close to the irruption threshold. Second, immigrations between neighbouring populations can lead to a synchronization of cycling by reducing the delay between otherwise independently cycling populations. ▪ There are cases where the arrival of SBW moths from Quebec coincided with the establishment of novel populations and the initiation of focal epicentres. At the same time, it is important to underscore that not all immigration events result in expansion of the source outbreak, or irruption at the destination receiving immigrants. The propensity for dispersal-driven irruptions thus appears to depend on factors governing cycling behavior at the destination location.	▪ Climate change will alter thermal regimes, variability, and the frequency and duration of extreme weather events in the range of SBW. ▪ SBW is sensitive to climatic conditions and these conditions determine SBW's range limits. ▪ Synchrony with host plants is temperature dependent and is crucial for SBW survival. ▪ SBW supports a diverse community of natural enemies, which are also sensitive to climatic conditions. ▪ SBW outbreaks have shown recent northern expansion into naïve black spruce forests north of where outbreaks occurred in the past.

Affirmative Statement:	AS 5: SBW outbreaks increase risk of wildland fire	AS 6: SBW outbreaks can result in negative impacts on market and non-market forest values
Authorities of work on AS:	L.M. Johnston, Y. Boulanger	D.W. McKenney, E.S. Hope, V. Lantz
Key points:	▪ Fire and SBW outbreaks are both common disturbances in much of eastern Canada, and they are linked both directly and indirectly with each other. ▪ Damage from SBW can result in a buildup of fuel for fire to burn, and the changes to the physical fuel arrangement have the potential to dramatically increase fire risk at the stand level and, under certain conditions, can produce extreme fire behaviour. ▪ There appears to be a temporal lag of effects of SBW on fuel availability; a peak occurs several years after the end of the defoliation event, creating a "window of opportunity" for increased fire risk. ▪ The relationship is linked in many ways and can be modified by weather/climate, stand composition, fire regimes, fire suppression, and fuel or stand dynamics, changing seasonally or gradually with time. ▪ Better understanding of the SBW/fire relationship will be even more crucial in the future, with the dynamic changes that SBW, its hosts, and fire are facing due to climate change.	▪ SBW outbreaks reduce the available supply of merchantable spruce-fir fibre in affected forests, causing downstream (e.g., shift in supply of spruce products) and upstream (e.g. stand harvest implications) economic impacts. ▪ From an economic perspective, SBW should be managed when the benefits of management efforts exceed associated costs. ▪ Economic considerations should include pest population dynamics, market values, feasible treatment strategies, harvest scheduling, the prioritization of optimal stands, and the associated ecosystem benefits of affected forest areas. ▪ Economic considerations can be expanded to include non-market values, including, for example, ecosystem services, carbon sequestration, and habitat provision. These non-market values can provide additional support for SBW management. Quantifying non-market values is an on-going process, and subject to significant uncertainty for both validity and reliability.
Affirmative Statement:	AS 7: Ecosystem integrity is generally resilient to natural SBW outbreaks but will alter ecosystem properties at shorter temporal and spatial scales	AS 8: SBW outbreaks will significantly affect cultural services of critical importance to rural and Indigenous communities in managed and protected areas
Authorities of work on AS:	L.A. Venier, M. Stastny, C.B. Edge, and J.J. Bowden	J.J. Bowden, D. Churchill, C.C. Sponarski, M. Stastny
Key points:	▪ SBW outbreaks are an important natural disturbance across large areas in Canada and region-wide outbreak suppression is expected to remove or reduce the natural, periodic imprint of SBW outbreaks not only on the age structure, composition, and regeneration of individual stands, but also on forest heterogeneity on the landscape, with poorly understood consequences on forest ecosystems. ▪ Anthropogenic change (e.g., climate change, harvest, introduction of non-native species, and post-SBW salvage logging) can interact with natural disturbances like SBW to move a system outside of its natural range of variation, with significant effects on biodiversity, nutrient cycling, and carbon sequestration. ▪ The pulse of SBW larvae during outbreaks supports the entire bird community, and the pulse of deadwood resulting from tree mortality supports saproxylic beetles that contribute to decomposition and to nutrient cycling, and that act as a key food source for birds and mammals. Salvage logging following SBW reduces the quantity of fresh deadwood, which in turn alters the saproxylic insect community, and reduces foraging and nesting opportunities for bark gleaners and cavity nesters. ▪ Through a suite of changes associated with SBW defoliation (i.e., litterfall, canopy openness, tree growth and mortality, coarse woody debris, as well as stand dynamics), outbreaks have significant consequences for biogeochemical processes in affected forests on various timescales. ▪ A decrease in net ecosystem productivity (NEP) may convert boreal forests from C sinks into C sources after SBW outbreaks. However, some models have shown a rapid recovery trend in annual NEP if defoliation was reduced, suggesting that affected forests may return to acting as a C sink faster if defoliation intensity is not severe and long-lasting.	▪ Forests provide a plethora of cultural ecosystem services that are often overlooked or inadequately captured in ecological and economic assessments of SBW impacts. ▪ These services are of immense importance to Indigenous and other rural and remote communities who live in or near areas that experience or have recently begun to experience SBW disturbance, as well as to other Canadians who visit these areas for recreation. ▪ Rural and remote communities represent nearly 20% of Canada's population and nearly 30% of Canada's GDP, largely supported by natural resources. ▪ Forest disturbances by insects, in some cases compounded by climate change, can alter forest ecosystems and the way people interact with rural landscapes. ▪ SBW outbreaks may shift in their intensity or geographic distribution due to anthropogenic drivers such as climate change, and protected areas that have not experienced this level of disturbance previously may also become affected. In these areas, the cascade of ecological effects triggered by novel outbreaks is more difficult to predict but is likely to lead to more severe or long-lasting consequences on cultural services.
Affirmative Statement:	AS 9: Current monitoring methods and intensities are adequate for effective management of SBW	AS 10: There are essential elements and principles of the EIS that must be included for a successful approach to managing SBW
Authorities of work on AS:	R.C. Johns, D. Carleton, J.P. Brandt	R.C. Johns, J.J. Bowden, E.R.D. Moise
Key points:	▪ For the FPS, current monitoring techniques meet provincial SBW management needs and have been used for several decades by these provinces. ▪ For the EIS, intensive monitoring of L2 densities has permitted the effective detection and subsequent suppression of 'hotspots' in Atlantic Canada.	▪ The EIS is essentially a proactive, large-scale approach intended to prevent outbreak rise and spread by detecting hotspots and identifying priority areas for SBW treatment with insecticides. ▪ Although monitoring approaches are similar, sampling intensity and action thresholds used to define treatment areas in the EIS differ substantially from the FPS. ▪ The basic protocol for defining treatment priority areas in the EIS involves: (1) detecting hotspots early; (2) assessing forest susceptibility; and (3) selecting and assigning control tactics. ▪ Efficacy under the EIS entails using tactics that can "add" SBW mortality through insecticide application to that occurring naturally while having a limited impact on natural mortality agents. ▪ Other important elements of the EIS include cost-benefit analyses, and communications and outreach to ensure public support for the program.

Affirmative Statement:	**AS 11: Sustained application of the EIS for the short-term (~5 more years) will reduce the long-term impact of SBW in Atlantic Canada**	**AS 12: Multiple management approaches are required for reducing SBW risk in different jurisdictions where different management goals and forest contexts exist**
Authorities of work on AS:	J.J. Bowden, E.R.D. Moise, R.C. Johns	J.J. Bowden, E.R.D. Moise, R.C. Johns
Key points:	▪ Currently, there is no evidence that the EIS applied in the short term will reduce long-term outbreak progression. ▪ There is compelling evidence that in the short term SBW populations are reduced by hot-spot treatment, with SBW densities in northern New Brunswick consistently and substantially lower than in nearby Quebec (employing a different management strategy – the FPS). ▪ Long-term data will ultimately be required to determine the long-term impacts of the EIS in Atlantic Canada. ▪ Recent experience suggests that the EIS is an effective strategy for flattening the outbreak curve and preventing outbreak spread in Atlantic Canada with a much-reduced overall treatment area in New Brunswick in particular.	▪ Forest structure has a significant influence on SBW defoliation, where increases in balsam fir content (and concurrent decreases in hardwood content) result in increased damage. ▪ SBW outbreaks are fueled by mass moth dispersal from adjacent regions undergoing an outbreak, with immigrants augmenting local reproductive output and facilitating escape from control by natural enemies (predators that feed upon SBW). ▪ Even when the EIS is considered a feasible approach, urban spaces, proximity to water bodies, privately-owned land and protected natural areas all present logistical challenges to the implementation of SBW management. ▪ Additional logistical challenges include limited road access to forest stands in many jurisdictions, necessitating sampling by other more costly and logistically challenging means (e.g., helicopter). ▪ Newfoundland, as a northern island, is relatively low in biodiversity and, therefore, there likely exists a lower diversity of natural enemies to attack rising populations of SBW. Community interactions can also be indirect via other co-occurring herbivores (e.g., introduced species) and exacerbate impacts.

Affirmative Statement:	**AS 13: An FPS can reduce SBW impacts but will not significantly alter the timing, duration, or locations of the outbreak**	**AS 14: Pre-emptive harvest and salvage logging are alternative approaches for SBW management**
Authorities of work on AS:	B.J. Cooke, P. Therrien, L. Morneau	B.J. Cooke, P. Therrien, L. Morneau, J.P. Brandt
Key points:	▪ Evidence exists for the continued efficacy of *Bacillus thuringiensis* var. *kurstaki* (*Btk*) or tebufenozide against SBW, and there is also abundant evidence that SBW larval populations may be reduced to levels where sufficient foliage is protected to keep host trees alive, even during intense outbreaks that last for many years. ▪ Operationally treated areas are typically small, in the order of tens to hundreds to thousands of hectares. During the last outbreak in Quebec, no more than 4–5% of the province's forests were sprayed for SBW. Although budworm populations are reduced by an FPS in these treated areas, the areas are never large enough to have any substantive impact on the wider SBW population. ▪ Some outbreaks collapse even when the forest is not heavily damaged, and substantial evidence indicates that rising late larval mortality caused by specific natural enemies, along with microsporidian disease are critical to such collapses. Thus, the greater the role of natural enemies in regulating SBW population cycles, the lesser the role of SBW-induced forest decline, and the less likely that spraying insecticide mid-outbreak prolongs the outbreak.	▪ Integrated pest management considers the full suite of strategies and tactics available for managing pests such as SBW, and pre-emptive harvesting and salvage logging are two viable alternatives. ▪ There are economic and ecological considerations associated with both pre-emptive harvesting and salvage logging, and these should be weighed carefully to select the most appropriate option and to ensure that sustainable forest management objectives are met. ▪ From an economic standpoint, pre-emptive harvest and salvage logging can represent an economic opportunity, but also an economic risk, depending on the scale of the outbreak, mill and product considerations, and market conditions. ▪ From an ecological standpoint, pre-emptive harvest and salvage logging should be conducted to minimize any negative ecological effects for present landscapes, and to ensure that forest management prescriptions now do not lead to enhanced SBW susceptibility and vulnerability of future forests when the next outbreak cycle arrives. ▪ Optimal decision-making requires robust data and information regarding all alternatives.

Affirmative Statement:	**AS 15: All SBW insecticidal treatment options have some impact on non-target organisms**
Authorities of work on AS:	V. Martel, J.J. Bowden, E.R.D. Moise
Key points:	▪ Commercially available SBW insecticides (registered under the *Pest Control Products Act*) that are based on either *Bacillus thuringiensis* var. *kurstaki* (*Btk*) or tebufenozide affect lepidopteran larvae that are feeding at the time of applications. ▪ In treatments against SBW, only forests with a high balsam fir and spruce content (i.e., forests most susceptible to SBW) are sprayed, and, therefore, spatial limitations further restrict non-target impacts. ▪ Recent research has shown no affect on lepidopteran abundance and richness from insecticide treatment (both *Btk* and tebufenozide) applied within the EIS context in New Brunswick the year of treatment or one year later. ▪ At realistic concentrations of *Btk* and tebufenozide, there is little or no effect on aquatic biodiversity. ▪ Because parasitized SBW larvae feed less than healthy larvae, and the insecticides must be ingested to be effective, parasitized larvae are less likely to be killed by insecticide treatment.

Risk Characterization

Our characterization of risk applies generally to the eastern range of SBW, from Ontario east to the Atlantic provinces, but not at the level of specific forest stands. Risk is also described qualitatively and comparatively, rather than quantitatively. Temporally, our risk characterization refers to the next 10–15 years. We characterize risk based on likelihood of occurrence and consequences of occurrence.

Likelihood of occurrence

Likelihood of occurrence here refers to the occurrence of a SBW outbreak. We define an outbreak as a buildup in abundance of SBW that causes sufficiently high defoliation across a large area that can be observed during aerial detection surveys. In characterizing likelihood, we use evidence and uncertainty summarized below and described in detail in the full report. We attempt to answer the questions "where will outbreaks occur and when?" and "what can be (or is being) done to prevent them or minimize their probability?"

Where will outbreaks occur and when?

SBW outbreaks currently occur in many regions of eastern Canada. It is likely that these outbreaks will continue and increase in extent to other susceptible areas nearby in the next few years. The ultimate northern extent of the outbreak in Quebec will reach farther north than prior outbreaks (see AS 1 in full report). The EIS is not effective against a well-established outbreak like the one currently occurring in large areas of Quebec (AS 2, AS 10, AS 12). Although it began recently, the outbreak in eastern Ontario near the Quebec border will intensify and grow in extent, and may occupy an area similar in size to previous outbreaks in that region. Changes in forest composition toward higher hardwood content and reduced susceptible spruce-fir content in western Ontario and western Quebec have happened during the past 35 years. Outbreaks, although still expected to occur, will likely occupy a smaller area overall than in the past. Temporally, the outbreak in western Ontario will likely lag behind the rest of the province, in terms of both outbreak initiation and collapse, by around ten years.

What can be (or is being) done to prevent them or minimize their probability?

The irruptive nature of SBW outbreaks, which is an important part of the EIS theory, is probably scale dependent, but there is high uncertainty about this dependency and therefore the preventability of outbreaks (AS 2). It is likely that the feasibility of preventability is reduced as the area-wide population cycle rises in the surrounding regions (AS 2). Due to the effectiveness of the EIS thus far (AS 11), we expect that New Brunswick will not reach an outbreak level if the EIS continues to be applied in the same manner for the next few years. Beyond that time frame, if the EIS ceases, the likelihood of an outbreak occurrence is currently not known. Cessation of the EIS now would likely result in the development of an outbreak in northern New Brunswick because of moth migration from Quebec, which is still significant in that area (AS 3). Populations in Cape Breton, Nova Scotia, are beginning to rise. This development lags behind New Brunswick by a few years. If the EIS is applied as in New Brunswick, one would expect a similar low risk as described above. It is possible, however, that repeated long-range dispersal of moths from Quebec into Cape Breton could increase the risk in Nova Scotia (AS 3). Also, if the EIS were to be terminated in New Brunswick, the expected development of an outbreak in northern New Brunswick would likely increase population pressure in Nova Scotia.

Long-distance dispersal can be important to outbreak development and spread (AS 3). The high populations, the large geographic extent of the outbreak, and the prevailing winds in eastern Quebec make it a likely source of long-distance moth dispersal to more easterly provinces. Thus, northern New Brunswick, western Newfoundland (island) and northeastern Nova Scotia (Cape Breton) are the likely recipients of such moth immigrants (AS 3). Early detection and response to mass immigrations is key for an effective EIS, and sustained prevention requires post-immigration treatment (AS 3, AS 10). Populations have grown quickly on the western side of the island of Newfoundland. Insecticidal treatments under an EIS have been applied for several years, but the effect on outbreak development is largely unknown. The controlling influence of natural enemies on SBW in Newfoundland and Labrador is also not yet known (AS 12). If it is less than in New Brunswick and other regions of Canada, we would anticipate a greater likelihood of an outbreak on the island of Newfoundland than in other Atlantic Provinces. Although Prince Edward Island may receive migrant moths through long-range dispersal, populations of SBW will likely remain low (i.e., below the irruptive threshold) due to the limited extent of spruce-fir forests on the island. No outbreak is expected in the latter province.

In areas where an FPS, salvage harvest and/or pre-emptive harvest is being applied, these actions will not change the trajectory of an existing outbreak (AS 12, AS 14). Monitoring currently undertaken by provinces to inform any of the latter management approaches appears sufficient to meet their objectives (AS 9). If monitoring for hotspot detection in a particular jurisdiction targeted for an EIS is insufficient to detect small but growing populations (i.e., irruption threshold), then the EIS may fade as a valid management option as populations increase beyond the suppression capability of such a strategy (AS 2, AS 3, AS 9).

Consequences of occurrence

In characterizing risk due to consequences of occurrence, we attempt to answer the questions: What will outbreaks do to spruce-fir forests and the value we derive from them? How will mitigation activities affect the consequences of outbreaks?

What will SBW outbreaks do to spruce-fir forests?

Loss of commercial volume. All areas in eastern Canada that experience multi-year outbreaks will lose commercial spruce-fir volumes through mortality and growth loss. Such losses will affect fibre supply to nearby mills (AS 6). Susceptibility and vulnerability vary among host tree species and among forest stands, depending on the proportions of various host species in those stands. Balsam fir and white spruce are the preferred hosts, followed by red spruce and black spruce. Balsam fir is also more vulnerable. Thus, the higher the proportion of balsam fir in a particular stand, the greater the impacts. Tolerance for such impacts will vary regionally (AS 6). Regions with an underutilized timber supply are more likely to absorb such timber losses because other non-damaged or less-damaged areas can be harvested instead (AS 6). Most susceptible areas in Ontario, Nova Scotia and Newfoundland fall into this category. On the other hand, New Brunswick, which has a fully committed timber supply, cannot absorb losses, and unmitigated outbreaks will directly affect the province's forest industry. Quebec falls somewhere between the two cases.

Altered fire risk. There is a clear but complex relationship between outbreaks and wildland fire risk (AS 5). Dead balsam fir stands will increase frequency and/or size of burned areas in most parts of eastern Canada that are susceptible to SBW outbreaks (AS 5). This risk will tend to lag behind SBW-caused mortality by a few years. The changing climate and associated future weather patterns are expected to increase the complexity of the SBW-fire relationship, making assessment of risk more difficult (AS 5).

Impacts on ecosystem dynamics. Reduction in carbon sequestration by forests is possible, as SBW outbreaks can convert areas from carbon sinks to carbon sources (AS 7). This is likely in areas with no SBW management. For areas where SBW outbreaks occur periodically, ecosystem integrity is expected to be resilient to outbreaks in the long term, but short-term negative effects on some ecosystem goods and services (such as immediate successional changes, a decrease in net ecosystem productivity (NEP) and the resulting decrease in carbon sequestration) can be expected (AS 7). In most of eastern Canada, SBW outbreaks are an intrinsic component of forest dynamics, and therefore we expect such ecosystems to be resilient across long timescales if outbreaks occur within the range of natural variability and do not interact negatively with other disturbance agents or factors (AS 7). Immediate successional effects will vary with pre-outbreak stand characteristics and may be pronounced. It is important to note that as it shapes and maintains the forests, this natural disturbance is considered intrinsic to the definition of their ecosystem's integrity, rather than affecting it. Novel habitats (not adapted to SBW due to climate change-driven northern range expansion of the insect), however, are likely to be more susceptible to damaging effects and may also transition to an undesirable forest type (AS 4, AS 7, AS 8). Biodiversity changes caused by SBW in most of its traditional range are expected to be within the natural range of variability (AS 7). With the expected shift/expansion of SBW outbreaks to regions farther north, we expect increased impacts on cultural services for Indigenous and rural communities, and in protected areas (AS 4, AS 8). The nature and severity of these impacts are largely unknown but are likely to increase in the long term as climate continues to change (AS 4). Negative impacts to elements of forest ecosystems (both direct and indirect) from SBW aerial application programs, either in an FPS or an EIS, are possible, but unlikely, because spray technology is vastly improved with respect to spray delivery, distribution and drift, and the insecticide products used have far fewer unintended effects than those used during previous outbreaks (AS 15).

Other potential impacts

Negative effects on the tourism industry are possible, especially in areas where outbreaks go unimpeded, such as national and provincial parks (AS 8).

How will mitigation activities affect the consequences of outbreaks?

In areas using an FPS for SBW, such as Quebec and Ontario, treated areas (including those where repeated applications may be required) will sustain some growth loss in balsam fir and spruce, but little mortality is expected in these areas during the course of the outbreak, especially in the less susceptible spruce (AS 13). Accordingly, all negative impacts in treated areas will be significantly less than those of an unmitigated outbreak. Salvage and pre-emptive harvesting strategies are expected to continue in Quebec and may begin in Ontario in areas not following an FPS (AS 14). As with all pest management strategies, the intent would be to meet forest management objectives and mitigate negative consequences (AS 10 - 14). It must be noted that only a small percentage of the defoliated areas in these provinces are treated relative to the total area of the outbreak, but these forests are also the most productive and important for other ecosystem goods and services.

Risks arising from interaction with climate change

The SBW system is sensitive to many climate-related factors making it likely that changing climate will exert multiple influences during the coming decades (AS 4). The spruce-fir-SBW system is likely to change but these medium- to long-term changes are difficult to predict. The changes will probably affect both the likelihood of occurrence of outbreaks (e.g., outbreaks occurring with greater frequency and in novel, northern forests), and the consequences of such occurrences, such as higher impacts to black spruce forests (as the phenology between host and insect becomes better matched) (AS 4).

Reducing uncertainties described by collecting additional baseline data and monitoring changes through time will result in a greater capacity to characterize future risk under climate change (AS 4). Short-term fluctuations in the spruce-fir-SBW system because of climatic change can lead to ecosystem surprise by generating temporary disruptions to equilibrium between spruce-fir forests, SBW, and climate, which, taken together, could move these systems to a new forest type.

Risk levels

We assess risk according to a gradient from low to high and differentiated by region, as warranted. We evaluate the risk levels for each province in turn in Fig. 2 (adapted from Fig. 7 in the full report).

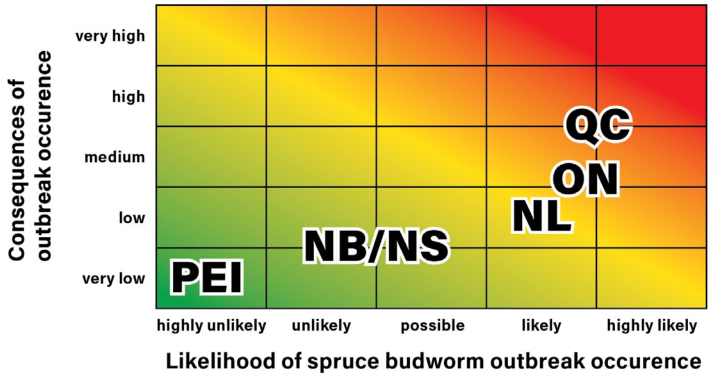

Figure 2. Risk matrix showing the level of risk for each province during the next 10–15 years given the expected SBW management strategy/actions.

Under the current EIS in New Brunswick, the province is at low risk of a SBW outbreak because populations remain endemic and below an irruption threshold. If populations exceed the threshold or there is a pivot to an FPS as an alternate approach, risk increases to medium-high, and the outbreak would be expected to move across the province during the next few years and threaten the fully allocated timber supply. Growth loss and mortality may be greater than in previous outbreaks, as it is unlikely that province-wide application of insecticides (as was done during the previous outbreak) would occur, due to high costs and potential negative public perceptions of insecticides. Rather, applying an FPS to the highest-priority areas is more likely. A switch to a policy of no SBW treatment (i.e., allowing an unmitigated outbreak) in the province's forests is considered highly unlikely and is not assessed here.

Nova Scotia is a partner in the EIS as part of the Healthy Forest Partnership (healthyforestpartnership.ca) and is expected to apply the EIS if populations warrant. As such, the risk here is low. If long-distance mass dispersal of moths results in increasing populations in the province, the risk would remain low if the EIS can be applied in Nova Scotia as in New Brunswick. If an FPS is implemented instead, then the risk increases to medium. Less susceptible forests and a less utilized timber supply in Nova Scotia also account for the slightly lower risk than in New Brunswick.

The province of Newfoundland and Labrador is applying the EIS on the western parts of the main island on provincial crown land but not in Gros Morne National Park, which has a different management paradigm. The efficacy of the EIS in western Newfoundland remains to be determined as it is premature to detect management effects. The area of susceptible forest on the island is substantial, so the potential impact of an outbreak on forest ecosystems would likely be large. With significant uncertainty, it is expected that the level of risk in Newfoundland and Labrador is higher than in New Brunswick and Nova Scotia but lower than Quebec and Ontario (described below).

Prince Edward Island may receive immigrant moths through long-range dispersal from Quebec or New Brunswick if populations were to rise there, but it has a very low risk of a SBW outbreak due to the relatively small quantity of susceptible spruce-fir forests on the island. Thus, current low SBW populations, along with the success currently being achieved by the EIS in New Brunswick, is expected to keep population pressure (and risk) on PEI quite low.

Quebec has extensive areas of susceptible forests and has been experiencing a widespread outbreak since 2006 across much of eastern and western parts of the province. Although the outbreak appears to have peaked in eastern regions of Quebec and may begin a declining phase back to endemic population levels, several more years of significant defoliation are likely (especially western Quebec), making the risk high in the traditional SBW-affected areas and also medium in the north, where timber losses will be less commercially significant, but potential ecological impacts may be greater.

Ontario also has extensive areas of susceptible spruce-fir forests. The outbreak areas in northeastern Ontario and western Quebec are parts of the same outbreak, spanning the provincial border. The cycling of the population in western Quebec suggests that northeastern Ontario will be at medium-high risk for several more years. Northwestern Ontario has a medium risk that may nonetheless be lower than the last outbreak's due to changes in forest composition since that time. This will result in reduced outbreak intensity along with a time lag of ten or more years compared to northeastern Ontario. Population pressure will be internal because the area of likely hotspots is extensive. Additionally, the current outbreak in Minnesota could provide a potential source of immigrant females. In southern Ontario, because of the more recent collapse of the previous outbreak in this region, we do not expect another outbreak in the next 10–15 years.

Knowledge Gaps

During our risk analysis process, we identified important knowledge gaps that need to be filled to reduce uncertainties associated with SBW risks and knowledge. Table 2 provides a summary of 15 of the most important knowledge gaps related to each affirmative statement discussed and reviewed as part of that process. These affirmative statements and their associated knowledge gaps can be used to identify priority areas for research. Rising to the top is the recognition that understanding population dynamics is critical to developing appropriate SBW management policies and practices. In particular, it is critical that we better understand what mechanisms suppress and maintain populations at endemic levels, what factors or changes lead to irruptive populations, and what causes the collapse of outbreak populations. These insights are essential for predicting the timing, location, severity, duration, and impacts of SBW outbreaks. It is also essential when selecting management options: EIS, FPS, salvage harvesting, pre-emptive harvesting, accelerated harvest, or no action.

Related to the previous mechanisms is the role of SBW moth dispersal in outbreaks. We need to have a clearer picture of whether outbreaks irrupt on their own across the landscape, or whether moth migration seeds, accelerates, or synchronizes local population increases that coalesce into large regional outbreaks. We also need to know at what scale these interactions are occurring. Such understanding gives greater confidence in selecting appropriate management strategies.

Indeed, a better understanding of how the interactions in the SBW system affect the health and resiliency of spruce-fir forests will lead to better forest management policies and practices. These interactions include the natural components of the system, such as wildfire, climate, birds, decomposers, small and large mammals, aquatic systems, species-at-risk, soils, and carbon sequestration (i.e., ecosystem goods and services). This understanding must also consider the effects of the management tactics on the overall health and resiliency of forest ecosystems, and the continuum of spatial and temporal scales, from individual stands to landscapes, and short- to long-term, at which SBW management may impact different components of ecological functioning.

SBW management and broader forest management will benefit from more comprehensive understanding of the costs and benefits of the available options. The costs and benefits to be considered include economic, social, and ecological. Critically, this also includes the costs and benefits of taking no action. Knowing the relative effectiveness and consequences of the various SBW management options is critical in deciding upon which option, or combination of options, are most likely to provide the most favourable cost-benefit ratio and the desired outcomes. One overriding theme in this risk assessment is the comparison between an EIS and an FPS. Other options, such as salvage harvesting or accelerated harvest, should also be considered. Resource managers need to be able to make informed decisions prior to outbreaks, or at least in the early stages of an outbreak, on which tactics to deploy, when, where, for how long, with what resources, at what cost, and at what scale.

A final and still significant research need is the implications of climate change. Its inherently high uncertainty has the potential to affect all the other questions raised in this risk assessment. It could also disrupt and alter the SBW system so much so that our current understanding of SBW ecology and management is no longer accurate or applicable. Research towards closing SBW knowledge gaps is critical to improving forest management in the face of this insect's outbreaks and minimizing future negative consequences while maintaining long-term forest resiliency.

Table 2. Many uncertainties were identified during the risk assessment process related to SBW outbreaks. The following itemizes elements that need to be addressed to reduce uncertainties related to affirmative statements discussed and reviewed as part of that process, ranked in order of priority. Additional elements requiring further research for individual affirmative statements are listed in the full report.

Affirmative statement	Reducing uncertainty	Authorities identifying the knowledge gap
AS 1: SBW outbreaks are periodic in occurrence and the mechanisms of population irruption are well understood	Determine the mechanisms of population irruption for endemic populations.	B.J. Cooke, J. Régnière, J.-N. Candau
AS 2: SBW population irruptions are preventable	Characterize the factors affecting the transition from focal epicenters to large-scale outbreak using synthetic spatial modeling and validation. So much of our "understanding" comes from theoretical ecology, as opposed to field measurement. This is an urgent area of research if we are to predict budworm risks in the 10–15-year time horizon.	B.J. Cooke, J. Régnière, J.-N. Candau
AS 11: Sustained application of the EIS for the short-term (~5 more years) will reduce the long-term impact of SBW in Atlantic Canada	Monitor, long-term, and evaluate the efficacy of the EIS in Atlantic Canada.	J.J. Bowden, E.R.D. Moise, R.C. Johns
AS 3: Long-distance dispersal of SBW moths is a major factor in outbreaks	Initiate ecophysiological research into factors governing take-off and capacity to sustain flight to improve forecasting the early part of the flight. Similar need exists for wing-folding and descent, followed by host-choice behaviour, particularly for night flight and when moths are forced down by convective storm fronts.	B.J. Cooke, J. Régnière, J.-N. Candau
AS 13: An FPS can reduce SBW impacts but will not significantly alter the timing, duration, or locations of the outbreak	Use and refine simulation models to explore the consequences of various assumptions about the role of natural enemies in the context of insecticide application because the role of natural enemies in precipitating collapse in sprayed stands requires increased attention.	B.J. Cooke, P. Therrien, L. Morneau
AS 10: There are essential elements and principles of the EIS that must be included for a successful approach to managing SBW	Examine the application of EIS principles across a range of jurisdictions, locations, and local outbreak intensities.	R.C. Johns, J.J. Bowden, E.R.D. Moise
AS 4: Climate change is altering the distribution, scale, and intensity of SBW outbreaks in the forests of eastern Canada	Quantify the impact of temperature (means, variability) on SBW's survival, physiology, and life history, particularly at range margins under future climatic conditions.	A.D. Roe, D.S. Pureswaran, J.J. Bowden, J. Régnière, E.R.D. Moise, V. Martel
AS 7: Ecosystem integrity is generally resilient to natural SBW outbreaks but will alter ecosystem properties at shorter temporal and spatial scales	Quantify the long-term impacts of SBW outbreak suppression on forest ecosystems that have evolved under a SBW disturbance regime in the context of climate change	L.A. Venier, M. Stastny, C.B. Edge, and J.J. Bowden

Affirmative statement	Reducing uncertainty	Authorities identifying the knowledge gap
AS 6: SBW outbreaks can result in negative impacts on market and non-market forest values	Improve knowledge on attitudes, preferences, willingness-to-pay, and costs of SBW management alternatives. This should help identify and justify SBW management programs and engage the public, directly affected stakeholders, and Indigenous peoples on options, opportunities, and trade-offs.	D.W. McKenney, E.S. Hope, V. Lantz
AS 14: Pre-emptive harvest and salvage logging are alternative approaches for SBW management	Create better tools for (i) predicting future budworm levels and impacts on multiple values, and (ii) predicting ecological outcomes of proposed interventions.	B.J. Cooke, P. Therrien, L. Morneau, J.P. Brandt
AS 12: Multiple management approaches are required for reducing SBW risk in different jurisdictions where different management goals and forest contexts exist	Determine non-target and downstream consequences of the EIS versus a "no-management" strategy on forest community structure and function.	J.J. Bowden, E.R.D. Moise, R.C. Johns
AS 15: All SBW insecticidal treatment options have some impact on non-target organisms	Quantify the impacts of SBW insecticidal treatments on other lepidopteran species (spring-, summer-, and fall-feeding) depending on the strategy (EIS vs FPS), the treatment product (Btk vs tebufenozide), the spatial scale of application, as well as the frequency of treatments.	V. Martel, J.J. Bowden, E.R.D. Moise
AS 5: SBW outbreaks increase risk of wildland fire	Improve characterization of SBW fuel types and integrate these fuel types into operational tools and fuel maps through empirical research and monitoring.	L.M. Johnston, Y. Boulanger
AS 8: SBW outbreaks will significantly affect cultural services of critical importance to rural and Indigenous communities in managed and protected areas	Improve understanding of cultural services affected – or facilitated – by SBW outbreaks or their prevention, especially in rural and remote communities.	J.J. Bowden, D. Churchill, C.C. Sponarski, M. Stastny
AS 9: Current monitoring methods and intensities are adequate for effective management of SBW	Enhance understanding of what types or combinations of surveillance methods might be used to monitor remote locations in the context of both EIS and FPS (i.e., areas with no road access).	R.C. Johns, D. Carleton, J.P. Brandt

Conclusions

During the past 125 years, SBW has had a major impact on the practice of forestry; it is expected to do the same moving into the future as long as the insect continues to negatively affect forest management objectives. Management of SBW has evolved as our knowledge has increased. Pest or forest managers dealing with SBW outbreaks currently use a wide array of tactics. These tactics depend on the forest or land management objectives of a given area. There is also a recognition that there are both costs and benefits associated with SBW and its management. Thus, these need to be weighed carefully when making decisions on the most suitable management option, including no action, for an area.

Paradigms in forest management have also evolved. During the previous two outbreaks of SBW, forest management paradigms shifted from sustained yield management to multiple use management and, finally, to integrated forest resource management. More recently, forest management has focused on broader ecosystem sustainability and resiliency, a fuller range of ecological goods and services, emulation of natural disturbances, and ecosystem-based management. These latest paradigms work towards a broad range of goals, including the maintenance of biodiversity and the integrity and resiliency of ecosystems (in the face of disturbances) by reducing or minimizing gaps between managed and natural forests, while still providing for a variety of goods, including wood, and non-market services. Forests are valued for many reasons beyond timber, with biodiversity, carbon sequestration, and water quality and quantity being critical and current examples, especially in the context of global change. These spaces also hold cultural value to Indigenous peoples who hold knowledge about these ecosystems as well as use these forests for multiple purposes. Any management intervention for SBW should factor in these broad goals when deciding on the most appropriate management approach or approaches.

Ecosystem management implies taking into account the interactions among components of the ecosystem and how management actions might affect them. A key element to this understanding is that SBW is a natural component of spruce-fir forests. This is particularly true for the boreal and hemiboreal spruce-fir forests, where periodic SBW outbreaks are a major part of the large-scale disturbance patterns, along with fire and windstorms. These events also affect each other, adding to, leading to, or inhibiting each other. Indirect consequences of management actions (e.g., decreases or increases in balsam fir content following harvesting or wildfire suppression) can exacerbate or dampen these disturbances. Similarly, direct management, such as an FPS during SBW outbreaks or outbreak prevention through EIS, could affect ecosystem values, depending at what scale actions are taken. For an FPS, an important consideration is that although, in general, only a small area of forest is usually treated, this forest is generally the most productive and contains the most high-value timber. In the case of EIS, the SBW population pulse and its consequences are averted. Therefore, SBW management policy should consider the ecological risks of both managing and not managing SBW outbreaks.