

A bioeconomic approach to assess the impact of an alien invasive insect on timber supply and harvesting: a case study with *Sirex noctilio* in eastern Canada

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Abstract: This study presents a model that assesses the potential impact of a new alien insect species, *Sirex noctilio* Fabricius, on pine timber supply and harvest activities in eastern Canada. We integrate the spread of *S. noctilio* with a broad-scale growth and harvest allocation model. Projections of pine mortality range between 25×10^6 and 115×10^6 m³ over 20 years depending on *S. noctilio* spread and impact assumptions. Our model suggests Ontario could experience the highest, most immediate losses (78% of the potential losses across eastern Canada), with Quebec sustaining most of the rest of the losses over the next 20 years. Potential losses of \$86 to \$254 million per year are simulated after 20 years. The net present value of total harvest losses after 28 years of outbreak ranges between \$0.7 to \$2.1 billion. Adaptation policies decrease short-term losses by 46%–55% and delay larger harvest failures by 9–11 years. Without harvest adaptation, failures to maintain annual allowable cut levels may occur once the total area infested exceeds 15×10^6 ha. While better understanding and representing *S. noctilio* behaviour will involve a significant effort, there is a strong demand by policy makers for this kind of information.

Résumé : Cette étude présente un modèle qui évalue l'impact potentiel d'une nouvelle espèce d'insecte exotique, *Sirex noctilio* Fabricius, sur les stocks de bois de pin et les activités de récolte dans l'est du Canada. Les auteurs ont intégré la propagation de *S. noctilio* à un modèle de croissance à grande échelle et d'allocation de la récolte. Les projections concernant la mortalité du pin varient de 25×10^6 and 115×10^6 sur 20 ans selon les hypothèses de propagation et d'impact de *S. noctilio*. Leur modèle indique que l'Ontario pourrait subir les pertes les plus élevées très tôt (78 % des pertes potentielles de tout l'est du Canada) et le Québec, presque toutes les pertes à venir au cours de la période s'étendant sur les 20 prochaines années. Les pertes annuelles pourraient atteindre 86–254 millions \$ après 20 ans. La valeur actualisée nette des pertes totales de récolte après 28 années d'épidémie varie de 0,7 à 2,1 milliards \$. Des stratégies d'adaptation diminueraient les pertes à court terme de 46–55 % et retarderaient les pires récoltes de 9–11 ans. Sans adaptation de la récolte, l'incapacité à maintenir les niveaux de possibilité annuelle de coupe pourrait survenir lorsque la superficie totale infestée dépassera 15×10^6 ha. Bien que d'importants efforts restent à faire pour mieux comprendre et représenter le comportement de *S. noctilio*, il y a une forte demande de la part des décideurs pour ce type d'informations.

[Traduit par la Rédaction]

Introduction

The impact of alien invasive species on timber supply and harvest activities has been identified as one of the most immediate and potentially damaging threats to Canadian forests (Natural Resources Canada 2006). Unfortunately, there are few modeling frameworks to support spatially explicit impact assessments and often even fewer data to parameterize models. Spread, economic impact, and mitigation studies of alien invasive species are few (Khalanski 1997; Cacho 2005). The studies that do exist have, for example, estimated total

damage costs (Cook et al. 2007), measured the effectiveness of “slow-the-spread” programs (Sharov and Liebhold 1998; Sharov et al. 1998), and assessed particular spread control strategies (Shoemaker 1981; Wilman 1996; Knowler and Barbier 2000). Some studies have analyzed broad-scale economic impacts of exotic pest invasions by linking invasion risks with the empirical models of international trade (Costello and McAusland 2003; Barbier and Shogren 2004; Prestemon et al. 2006). These global models generally do not incorporate fine-resolution spatial and temporal information about invasion dynamics and host resources.

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While native forest pest studies often examine current and potential impacts on forest harvest levels (e.g., Conway et al. 1999; the recent mountain pine beetle outbreak, Patriquin et al. 2007; Phillips et al. 2007), assessments of alien invasive pests often overlook this issue. Furthermore, most calculations of damage costs from alien invasive forest pests apparently overlook possible adjustments of forest management practices and harvests.

Here we address the possible impact of an alien invasive species on the forest products sector with an integrated modeling approach that includes broad-scale spread and host interaction dynamics and quantification of biophysical and harvest-related economic impacts. Integrated simulation models offer the opportunity to better recreate the heterogeneous nature of forest landscapes and the pathways of pest spread and can be linked with existing harvest and wood supply allocation programs (Bettinger et al. 2002; Peter and Nelson 2005). This approach also offers a more accurate representation of potential damages and economic impacts specific to the forest sector and helps quantify the potential effectiveness of broad-scale harvest adaptation policies.

This study focuses on a new potential threat, *Sirex noctilio* Fabricius, a pine woodwasp (Haugen and Hoebeke 2005) detected in the United States in 2004 (Hoebeke et al. 2005) and in Canada in 2005 (de Groot et al. 2006). It is a major pest of pine plantations in the Southern Hemisphere and is considered a high risk to pine plantations and forests in North America (Haugen and Underdown 1990; Haugen 2006; Borchert et al. 2007; Corley et al. 2007). Currently, *Pinus sylvestris* L. is the species most noticeably affected, but native pine species such as *Pinus resinosa* Ait., *Pinus strobus* L., and *Pinus banksiana* Lamb. also have been attacked (Haugen and Hoebeke 2005; P. de Groot, unpublished data). *Sirex noctilio* has a broad bioclimatic distribution range and thus is likely to survive in most parts of the subboreal biome (Carnegie et al. 2006). Based on historical retrospective estimates from the Southern Hemisphere, the average natural rate of spread is likely in the range of 30 to 50 km-year⁻¹ (Haugen et al. 1990; Carnegie et al. 2006). Virtually all of the knowledge about the biology, ecology, and management of *S. noctilio* is from the Southern Hemisphere, where it is an alien invasive pest attacking exotic pine plantations.

Our main objective is to provide initial estimates of potential spread and help quantify possible physical and economic impacts of a *S. noctilio* outbreak on standing pine volume across eastern Canada. We recognize there may be considerable debate on the behaviour of *S. noctilio* in new landscapes, but this does not negate the need of forest policymakers and federal regulators for more detailed information on possible impacts. To help address at least some of the uncertainties, we use a stochastic spread model and generate several invasion scenarios that incorporate broad-ranging assumptions about the species' possible spread and impact. We present a relatively simple invasive species spread model embedded in an existing cost-benefit and harvest scheduling model (Yemshanov et al. 2007). The model links the stochastic spread patterns with spatially explicit pine volumes and current regional harvest targets. Thus our approach addresses, to some degree, the feedback between expansion of an outbreak and harvest opportunities at a broad scale.

Table 1. Maximum susceptibility ratings of pine species for the study area.

Species	a_{\max} (years)*	p_{\max} †
Natural forest		
<i>P. resinosa</i>	65	0.75
<i>P. strobus</i>	65	0.25
<i>P. banksiana</i>	65	0.95
<i>P. sylvestris</i>	50	0.95
Plantation		
<i>P. resinosa</i>	65	0.75
<i>P. strobus</i>	65	0.25
<i>P. banksiana</i>	65	1.0
<i>P. sylvestris</i>	50	1.0

* a_{\max} is stand age.

†The susceptibility (p_{\max}) values were determined via approximations from ordinal pine susceptibility rankings (USDA Forest Health Technology Enterprise Team 2007).

Methods

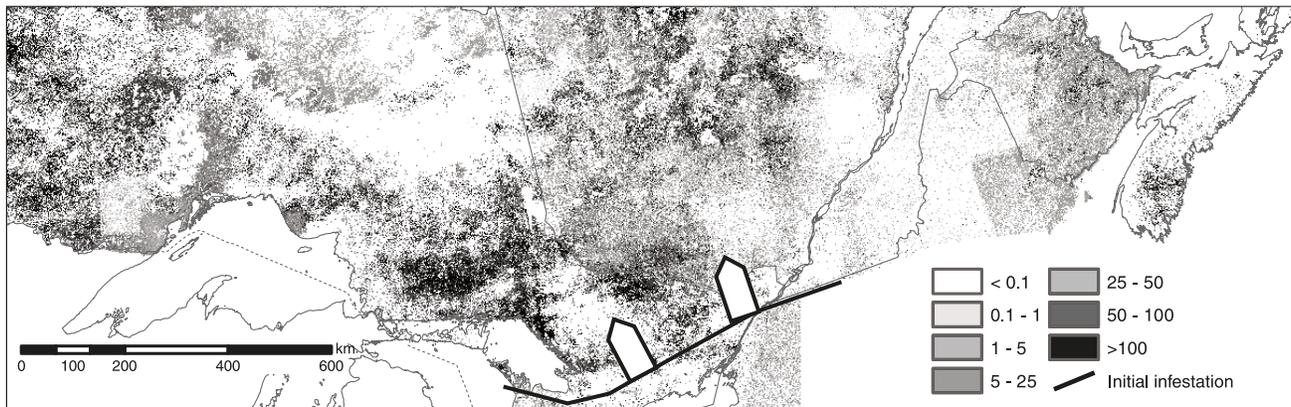
Overview of the model

The overall analysis takes place using the Canadian Forest Service Forest Bioeconomic Model (CFS-FBM). This model combines certain biophysical and economic analyses in one spatially explicit framework (Yemshanov et al. 2005, 2007; McKenney et al. 2006). For the current effort, CFS-FBM has been modified to include the following: (1) spread and survival of invading organisms and (2) pine growth and harvest allocations linked to representations of cash flows and present value calculations. The biophysical component simulates forest growth, timber yields, and basic forest management activities (e.g., planting and harvesting). The cost-benefit module uses the biophysical outputs and prices (such as silvicultural costs and standing timber values) to calculate timber supply costs and net revenues from forestry activities. Data have been developed and the model applied to simulate *S. noctilio* spread scenarios across Ontario, Quebec, New Brunswick, and Nova Scotia, and thus the model covers the majority of the industrial forest land base in eastern Canada.

Sirex noctilio spread and impact

For *S. noctilio*, few empirical or theoretical studies have been conducted to quantify the dispersal of individuals and spread of populations. *Sirex noctilio* can disperse naturally by adult flight or may be assisted by human activities (e.g., long-distance transport of infested logs). Estimates of natural spread have generally relied on detections at various locations through time but are somewhat limited and mostly focused on very fine spatial scales (Corley et al. 2007). These observations provided only a coarse indication of the natural spread of *S. noctilio* populations at broader scales because there is a considerable time lag between *S. noctilio* entering the area and its first detections. Because existing information about *S. noctilio* spread in Canada is poor, we used a more general approach similar to Sharov and Liebhold's (1998) model of gypsy moth (*Lymantria dispar* L.) in the eastern United States. We simulate spread as a traveling wave in a discrete two-dimensional landscape. This approach can reasonably capture both natural and human-assisted spread. The minimum spatial domain is a regular grid

Fig. 1. Standing pine volume (cubic metres per hectare; an aggregation of individual pine species maps). Line shows initial *Sirex noctilio* infestation based on a 2006 Canadian Forest Service – Canadian Food Inspection Agency survey. The US area bordering southern Ontario, Quebec, and New Brunswick was added to make the spread algorithm work correctly. However, the bordering US areas were excluded from the impact analysis. Block arrows show the direction of *S. noctilio* spread.



map cell. For any given cell, the colonization rate is calculated as a variable dependent on the distance from the nearest infested location. The colonization rate is a distance-dependent probability-density function, $f(x)$. While Sharov and Liebhold (1998) used a linearly decaying function, we use a nonlinearly decaying shape of $f(x)$, as this provides a better fit to a priori expectations:

$$[1] \quad f(x) = \begin{cases} \frac{p_0}{a + bx^c} & \text{for } x < x_{\max} \\ 0 & \text{for } x \geq x_{\max} \end{cases}$$

where p_0 is the colonization probability at the spatial resolution of our study, x is the distance from the nearest infested area (kilometres), x_{\max} is the maximum distance from an existing population at which a new population may become established, and a , b , and c are the coefficients that describe the shape of the colonization probability decay function, $f(x)$, through space. The coefficients were fitted to expert estimates with specific values, $a = 1.13$, $b = 0.096$, and $c = 1.492$.

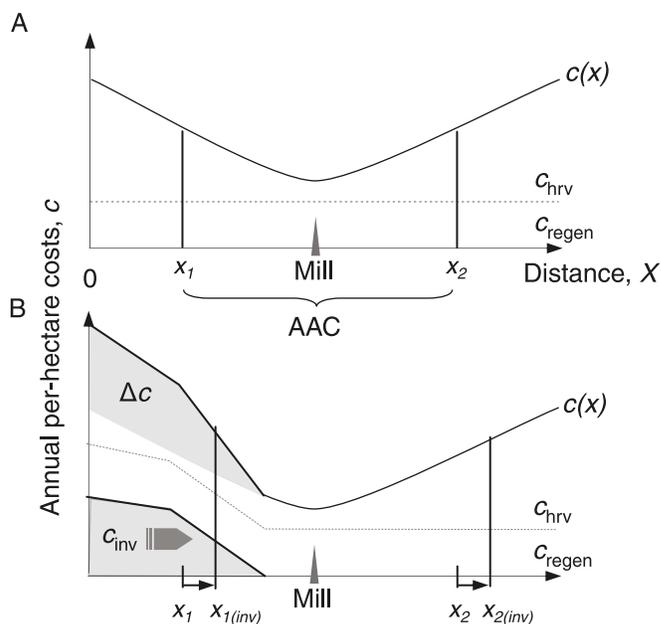
The total infested area and level of pine mortality are defined by p_0 values and the shape of $f(x)$ function ($\int_0^{x_{\max}} f(x) dx$ to be precise). The shape of the $f(x)$ function and the x_{\max} values were based on general experience in the Southern Hemisphere (Haugen et al. 1990; Carnegie et al. 2006) and, importantly, do represent an aggregated result of both human-assisted and natural spread potential. x_{\max} was set to $50 \text{ km}\cdot\text{year}^{-1}$. Because *S. noctilio* does not have a history of observations in Canada, we also must rely on expert estimates about *S. noctilio* local infestation potential. We have created two scenarios covering quite a broad range of p_0 values of 0.2 and 0.8. These values represent the probability of dispersal to the nearest adjacent map cells ($400 \text{ m} \times 400 \text{ m}$ cells in the current study).

For each individual map cell we assume that the number of individuals in a new “colony” (a population occupying a map cell) depends only on the colony age, a , in a cell i :

$$[2] \quad N_{i(a)} = N_0 R^a$$

where $N_{i(a)}$ is the number of individuals at colony age a , N_0 is the initial number of individuals after first establishment (N is measured in per-area units), and R is the net annual

Fig. 2. An illustration of invasion spread and the harvest dynamics response. (A) Harvest-only scenario (no invasion); (B) spread enters the harvest region. $c(x)$, cost function over distance; c_{hrv} , harvest costs; c_{inv} , costs associated with wood mortality; c_{regen} , regeneration costs; AAC, annual allowable cut.



reproduction rate. The maximum population size occupying a given map cell is limited by carrying capacity, K (again following Sharov and Liebhold 1998). The R value essentially defines the minimum time required for the population to reach a carrying capacity. With the assumption of a 4–5 year lag from establishment, the R values were set to 4. Little is known about the scale and spatial extent of possible Allee effects in *S. noctilio* populations in North America because of its recent discovery and the subsequent research emphasis on detection and biological control. Because of this lack of knowledge, and also because of the coarse resolution of this study, the Allee effect was not included in the present model. This will be incorporated in future work as more knowledge and data become available.

Fig. 3. Areas of primary harvest (APH) with unique annual allowable cut (AAC) values. Line shows initial *Sirex noctilio* infestation based on a 2006 Canadian Forest Service – Canadian Food Inspection Agency survey. Block arrows show the direction of *S. noctilio* spread. Shades of grey delineate individual APHs.

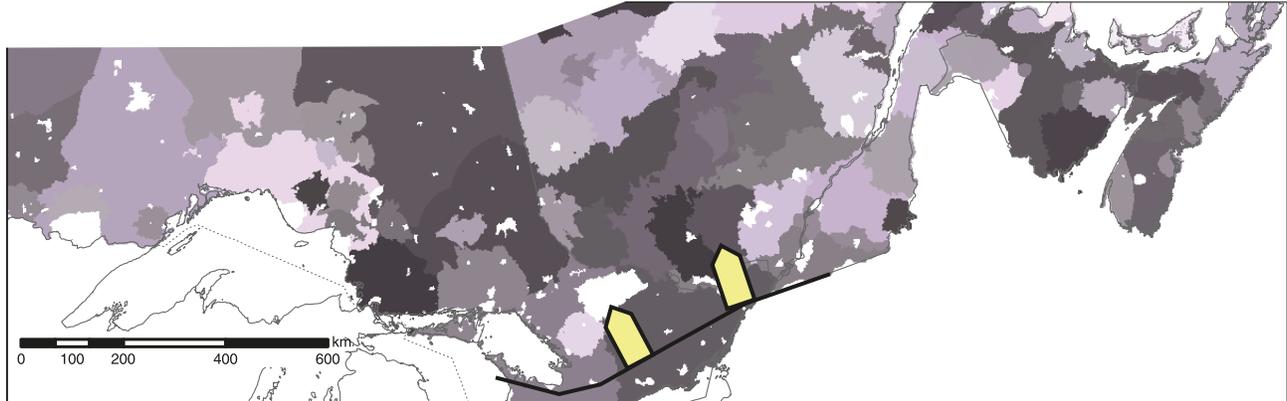
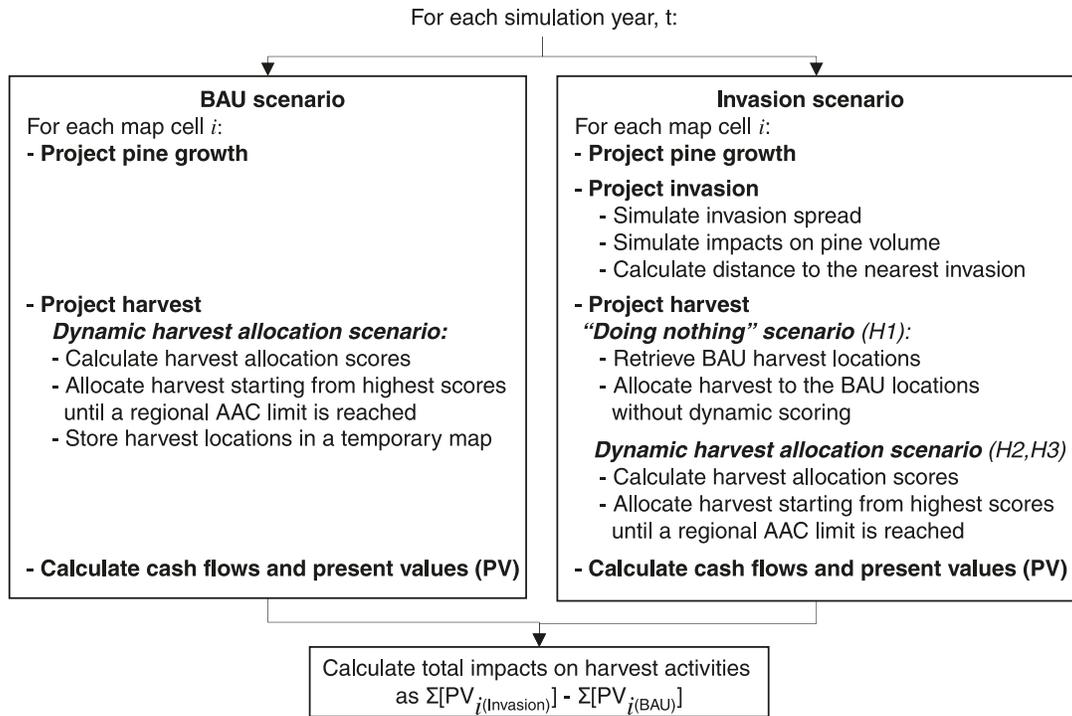


Fig. 4. Summary of the impact analysis on timber supply and harvest.



Sirex noctilio often has a 1 year life cycle, but it may take 2 or even 3 years to complete a generation, especially in cooler climates (Borchert et al. 2007). The duration of the life cycle is under investigation, and currently there are no data to determine the proportion of the populations with 1 and 2 year life cycles; we therefore assume a 1 year cycle. Thus, the model calculated unique $N_{i(a)}$ values for each individual map cell, i , on an annual basis.

The population model is used to estimate the potential volume of pine mortality caused by *S. noctilio*. To track this, we introduce a ratio, w , that represents the minimum volume of pine required to support a population at a given time step, t :

$$[3] \quad \begin{aligned} V_{i(t)} &= wN_{i(t)} && \text{for } N_{i(t)} < K \\ &= wK && \text{for } N_{i(t)} = K \end{aligned}$$

According to this process, the density of individuals in the established colony starts as geometric growth from N_0 with

the rate R until it reaches carrying capacity K . Note that total population size is also limited by the amount of pine available on a site at a given time step, t :

$$[4] \quad N_{i(t)} \leq \frac{V_{i(t)}}{w}$$

$K_w = V_{\max}$ can be calculated from the maximum rate of pine mortality. Previous estimates in Australian conditions, with a consideration of a tree size distribution of a typical pine stand, suggest that a massive *S. noctilio* outbreak could destroy as much as 80% of a pine stand over 15 years (the remaining 20% represents the most vigorous large-diameter trees in the upper canopy that usually survive attack). With the assumption of an average pine yield in unmanaged boreal and subboreal stands of $\sim 190 \text{ m}^3 \cdot \text{ha}^{-1}$, based on the Canadian Forest Service Forest Inventory Database (CanFI) (Gillis 2001), these estimates translate into a $\sim 10.1 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$

Table 2. Model simulation scenarios.

p_0	V_{\max}	Harvest scenarios	k_{timb}	k_d	Harvest allocation heuristic criteria
BAU scenario					
—	—	BAU	0.8*	—	Maximize PV(net timber returns)
Invasion scenarios					
0.2	0.8	H1	— [†]	—	Using harvest configuration from BAU scenario (no adaptation scenarios)
0.8	0.8	H1	—	—	
0.2	3	H1	—	—	
0.8	3	H1	—	—	
0.2	0.8	H2	0.8	—	Maximize PV(net timber returns)
0.8	0.8	H2	0.8	—	
0.2	3	H2	0.8	—	Maximize PV(net timber returns) and allocate harvest closer to infested locations
0.8	3	H2	0.8	—	
0.2	0.8	H3	0.2	0.6	
0.8	0.8	H3	0.2	0.6	
0.2	3	H3	0.2	0.6	
0.8	3	H3	0.2	0.6	

Note: p_0 is the local colonization probability; V_{\max} is the upper limit of pine mortality (cubic metres per hectare per year); and k_d and k_{timb} are weighting coefficients. PV, present value; BAU, “business-as-usual” scenario.

* $k_{\text{timb}} = 0.2$ for all scenarios.

[†]The scenario uses exact BAU harvest configuration.

upper limit of pine mortality for a pure pine stand. Recognizing that real outcomes for North American conditions do not yet exist and hence this value is very much an approximation, we use two alternative assumptions of $V_{\max} \approx 4.4$ and $16.7 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$. These represent lower and higher pine mortality rates. However note that these values are also adjusted by average *Pinus* spp. proportions. These proportions are approximately 18% in eastern Canada (based on the CanFI) and ultimately resulted in mean V_{\max} values of 0.8 and $3 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$. V_{\max} , in fact, acts as a constraint, and the actual mortality rates in a map cell vary depending on the amount of pine and the age of the *S. noctilio* infestation. Over large spatial scales, these assumptions result in a logistic shape of the physical impact as the infestation expands.

Pine stands also have different susceptibility to *S. noctilio* attacks. Susceptibility depends on tree attributes, such as species, age, diameter, and vigor. Trees under stress are more susceptible to attack. In the model, species susceptibility is portrayed as a species- and age-dependent probability-density function, p_v :

$$\begin{aligned}
 p_v &= 0 && \text{for } a < a_0 \\
 [5] \quad &= \frac{p_{\max} a}{a_{\max} - a_0} && \text{for } a_0 < a < a_{\max} \\
 &= p_{\max} && \text{for } a > a_{\max}
 \end{aligned}$$

where a_{\max} is the senescence age when susceptibility reaches its maximum, p_{\max} is the highest susceptibility value for senile and overstocked stands, and a_0 is the age of stand closure. Stand closure usually accelerates self-thinning and increases the number of suppressed trees in the lower canopy, hence making the stand more susceptible to *S. noctilio* attacks. The a_0 value was set to 20 years. The species-specific p_{\max} values were translated from the USDA Forest Health Technology Enterprise Team (2007) ordinal susceptibility ratings. The susceptibility values were used to estimate the

establishment probability for new *S. noctilio* colonies based on the local species composition and on the potentially vulnerable portion of pine stands that could be killed by a growing *S. noctilio* population. Higher susceptibility usually leads to more explosive *S. noctilio* population growth and higher host losses (especially at the early stages of invasion). Estimated a_{\max} and p_{\max} values are shown in Table 1.

The model tracks only established colonies of a minimum size equal to a map cell area. We also assume that the probability of colony extinction is very low and only occurs as a result of eradication activities (see Sharov and Liebhold 1998). The spread model is applied in 1 year time steps. For each map cell i , the model tracks the dynamics of $N_{i(t)}$, $V_{i(t)}$, p_v , stand age, and pine susceptibility and composition. Total standing volume is used to calculate potential pine mortality from *S. noctilio* infestation based on $V_{i(t)}$ and V_{\max} .

Pine volume, growth, and initial infestations

An important component of the present study is the representation of pine standing volume over the study region. Canada’s CanFI database was used as the basic source data for pine standing volumes and stand age. CanFI is a part of the Canadian National Forest Inventory (Gillis 2001) and provides coarse ($10 \text{ km} \times 10 \text{ km}$) spatial estimates of stand-level information aggregated from provincial management agencies. These data were integrated with a satellite land cover classification to produce $400 \text{ m} \times 400 \text{ m}$ resolution estimates of pine volume. The area of interest covers most of the active forest management zone within Ontario, Quebec, New Brunswick, and Nova Scotia (Fig. 1).

We used normal yield equations from Ung et al. (2009) to generate growth and yield projections. These models provide a consistent approach to generate the growth rates that could occur in the absence of *S. noctilio*. The map of initial infestation of *S. noctilio* was based on the detection survey conducted in Canada in 2005–2006 (de Groot et al. 2006) (Fig. 1). Based on 2005–2006 field observations, we esti-

mated that 25% of pine stands within this broad region would have *S. noctilio* populations. This factor converts the detection events into an approximate estimate of the existing *S. noctilio* population and compensates for the low detection rates of currently used *S. noctilio* traps.

Representing harvest impacts

The impact on timber harvests can be estimated by intersecting spread and impact projections with pine inventories (and growth) and anticipated harvest schedules in the absence of *S. noctilio*. However, the adjustment possibilities of timber harvest allocations through time should also be accounted for. Harvest adjustments are common in infested zones and usually chase spread patterns (e.g., outbreaks of the boll weevil, *Anthonomus grandis* Boheman (USDA Animal and Plant Health Inspection Service 1997), the emerald ash borer, *Agrilus planipennis* Fairmaire (BenDor et al. 2006), and the mountain pine beetle, *Dendroctonus ponderosae* Hopkins (British Columbia Ministry of Forests 2005)). Decisions about harvesting in areas with unanticipated disturbances are usually guided by multiple factors. Common questions include the following: When and where is it feasible to harvest infested stands? Is it feasible to reschedule harvests or is “do nothing” a better strategy? There are a variety of timber harvest allocation methods, including linear programming and optimization techniques (Murray 1999; Weintraub and Navon 1976; Hoganson and Borges 1998), real options (Saphores 2000), and various heuristic methods (Boston and Bettinger 1999; Bettinger et al. 2002). Linear programming and optimization usually require a deterministic representation of growth projections and timber supply data and are also fairly detailed with respect to forest management objectives (i.e., the parameter space). Adding infestations for alien invasive species creates a stochastically changing parameter space that severely restricts the use of optimization (Olson and Roy 2002). Recent techniques of dealing with stochastic disturbances include generating arrays of random patterns from stand-alone models, and then using these patterns with forest inventory maps and conventional harvest planning programs (Peter and Nelson 2005).

Given the large geographic scope and the stochastic nature of the present problem, we use scoring techniques to establish harvest allocations. These heuristic decision rules (e.g., harvest timber that is the shortest distance from the mill (Nelson et al. 1995)) are less computationally intensive and are defensible for the current problem. Importantly, this type of approach can be used in conjunction with stochastic spread models and is more suitable for large problems and coarse-scale analyses (e.g., when the knowledge about forest composition at the location of harvest sites is approximate).

Heuristic approaches work well with the annual allowable cut (AAC) concept. The AAC sets the maximum volume of timber that can be harvested annually in a forest management region without diminishing its biological production capacity. In Canada provincial land management agencies calculate AACs based on sustainable yields using integrated forest management models (e.g., the SFMM model in Ontario (Davis 1999), Sylva II in Quebec (ministère des Ressources naturelles du Québec 1997)).

Our model calculates the volume of growth, the area of infestation, and the volume of tree mortality for each time step. Harvest allocation scores, X_i , are calculated for individual map cells. The score values are ranked within each harvest region. Cells with the highest scores are allocated for harvest until the AAC limit is reached. Our scoring uses three possible criteria: (1) the present value of net timber revenues inclusive of silvicultural, harvest, transportation, and postharvest regeneration costs, PV_{timb} ; (2) the inverse distance to a nearest infestation front, $1/d_{\text{max}}$; and (3) a spatially uniform random variate, σ , $\sigma \in (0, 1)$, that represents other harvest criteria not correlated with [1] and [2] (see Boyland et al. 2005):

$$[6] \quad X_i = \sigma k_{\text{rand}} + k_{\text{timb}} PV_{\text{timb}} + \frac{k_d}{d_{\text{max}}}$$

where k_{rand} , k_d , and k_{timb} are weighting coefficients. The criteria $1/d_{\text{max}}$ is added to mimic harvest allocations close to an infestation front — it increases the relative score weights for locations in proximity to an infested area. Individual score values are recalculated annually for every forested site (map cell). Various general harvest policies can be explored via changing weighting coefficients k . While this simple model does not optimize operational harvest allocations at local scales, it provides a general approach to represent basic harvest responses to alien invasive pest outbreaks across larger landscapes.

Assessing economic impact on harvest

Our assessment of the economic impact of *S. noctilio* is from the perspective of changes in timber supply value delivered to the mill gate due to the invasion. The elements of this perspective include the volume and price of harvested logs, net of transportation costs to the mill gate. Economic outcomes are estimated using the concept of present value (PV), a metric commonly used in economic assessments of pest management programs over time (Leuschner et al. 1996; Sharov and Liebhold 1998). The total present value of timber supply is calculated as sum of PV’s of individual harvest blocks over a planning horizon, T :

$$[7] \quad PV = \sum_{i=0}^{N_t} \left[\sum_{t=0}^T \left(\frac{V_{\text{host}_i} [p_w (1 - k_{\text{host}_i}) - c_{\text{hrv}_i}] + V_{\text{other}_i} (p_w - c_{\text{hrv}_i}) - c_{\text{regen}}}{(1 + r)^t} \right) \right]$$

where V_{host_i} and V_{other_i} are the annual per-hectare volume of the host species and of other species, respectively, harvested at a given location, $i, i \in [1; N_t]$ (cubic metres per hectare); p_w is the timber price (dollars per cubic metre); c_{hrv_i} is the

value of harvest, net of transportation costs (dollars per cubic metre); c_{regen} is the postharvest treatment costs prescribed by provincial guidelines (dollars per hectare); r is the discount rate; and N_t is the total harvest area at a given

year, t . An infestation may downgrade the commercial value of standing timber. Hence a price depreciation factor, k_{host_t} , is included as a function of the density of invading organisms occupying a forest site:

$$[8] \quad k_{\text{host}_t} = k_0 \left(\frac{N_{i(t)}}{K} \right)$$

where $N_{i(t)}$ is the site population density, K is the total carrying capacity (see eq. 3), and k_0 is the price depreciation for a completely infested site. k_0 was set to 0.8 to represent a lower-grade pulpwood price. We are assuming that live trees on infested locations can still be used for low-grade pulpwood and (or) pellet production. We do not include dead trees in the harvest queue because of difficulties associated with estimating the size of, for example, future “bioenergy wood” markets. This issue could be examined in future studies, as it may decrease aggregate economic impacts.

Figure 2 illustrates the interactions between the spread of an invading organism and harvest allocations using a one-dimensional homogeneous transect $[0; X]$. Figure 2A shows the conditions before the infestation, and Fig. 2B, when spread enters the harvest region. For a given harvest year, the annual value of the cost function, $c(x)$, can be defined as the sum of net timber revenues, postharvest treatment costs (C_{regen}), and distance-dependent transportation and harvest costs (C_{hrv}). If V_{host_t} is assumed to be constant across the transect for simplicity, the AAC can be outlined by the interval $[x_1; x_2]$ where:

$$[9] \quad x_2 - x_1 = \text{const} \quad \text{and} \quad \sum_{x_1}^{x_2} [V_{\text{host}}] = \text{AAC}$$

A cost-minimization harvest strategy usually finds the solution that minimizes the integral of cost function, $\int_{x_2}^{x_1} c(x)dx$, with a unique allocation $[x_1; x_2]$ (represented in this simplified illustration as a continuous interval). When an infestation enters the harvest area, it changes the shape of $c(x)$ as a result of damage costs, c_{inv_t} (Fig. 2B), hence leading to a new harvest allocation, $[x_{1(\text{inv})}; x_{2(\text{inv})}]$. If we assume for simplicity that $V_{\text{other}_t} = 0$ and $V_{\text{host}_t} = \text{const}$ in the absence of invasion, the value of c_{inv} can be found as

$$[10] \quad c_{\text{inv}_t} = V_{\text{host}_t} p_w k_{\text{host}_t}$$

Note that the actual model uses maps of spread potential, pine volume (V_{host_t}), and harvest costs and generates harvest solutions in a two-dimensional setting.

Other important data requirements

Annual allowable cut levels

To estimate pine AACs, we used existing softwood mill loads and capacities. We divided the study area into 77 areas of primary harvest (APH) centered on large wood-processing facilities and groups of mills with total capacities of $1 \times 10^5 \text{ m}^3 \cdot \text{year}^{-1}$ or more (Fig. 3). Mill information was collected from a variety of sources, including company Web sites, communications with industry representatives, and government reports. We used annual volume consumption of softwoods to help define AACs for each APH. APHs represent nonoverlapping regions and characterize coarse-scale

spatial variation of the AAC across the study area. To define the APH boundaries, we used the following approach. First, total timber supply required to sustain the AAC (i.e., the number of map cells with pine) was calculated using annual mill consumption volumes and assuming an annual growth rate for conifers of $1.8 \text{ m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ (estimated from the CanFI) and an average 100 year rotation. This perhaps conservative growth-rate estimate was used to account for potential disturbances other than *S. noctilio*. Next, we started aggregating forested cells from the locations closest to the mill and progressed in an expanding radius around mill locations until reaching the AAC or the boundary of another APH. Some mills also may accept timber from the United States or locations outside of their APH when the local timber supply is too small to sustain the demand (e.g., mills in southeastern Quebec). In this case we decreased the AAC to match the timber supply available within the APH. As the AAC usually includes various sustainability criteria, we checked the ability of the existing forest to sustain regional AACs at least over two rotations (following Hegan and Luckert 2000). For each region, a pine fraction, AAC_{pine} , in the total softwood allowable cut, AAC_{sw} , was then estimated as:

$$[11] \quad \text{AAC}_{\text{pine}} = \frac{\text{AAC}_{\text{sw}} V_{\text{pine}}}{V_{\text{sw}}}$$

where V_{sw} and V_{pine} are the total standing volume for softwood species and pines, respectively, in a given forest management region.

Transportation, harvest costs, and timber values

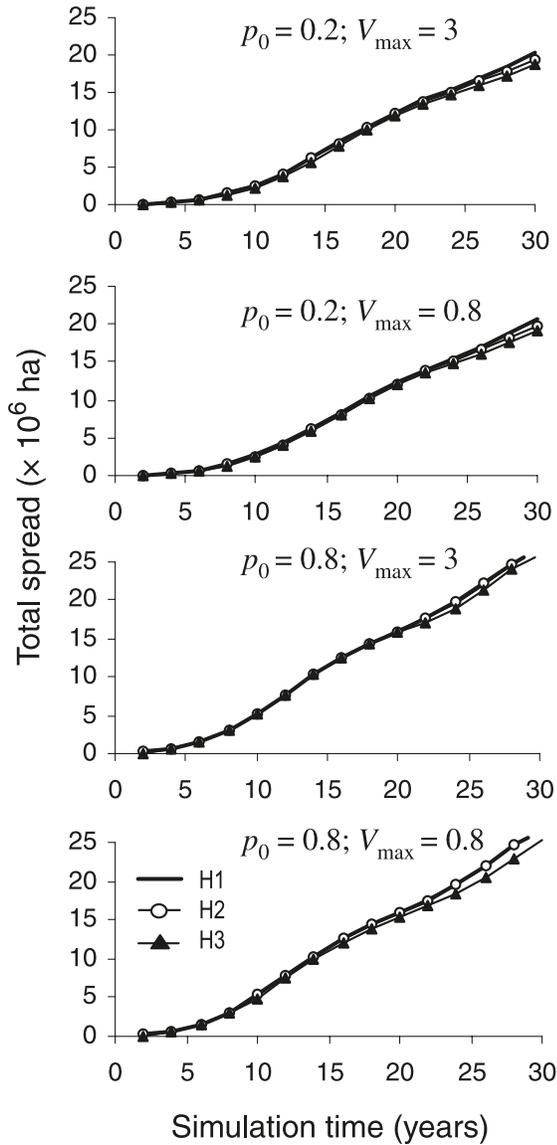
Average transportation costs were calculated using Forest Engineering Research Institute of Canada model principles (Gingras and Favreau 1996; Southern New Brunswick Wood Co-op Ltd 2007; see also Yemshanov and McKenney 2008). The average per-unit per-kilometre costs were set to $\$0.12 \cdot \text{m}^{-3} \cdot \text{km}^{-1}$. Geographical coordinates of mills were used to calculate the matrix of transportation distances. To simplify spatial calculations, the analysis does not include the potential of wood supply substitution via cross-provincial or international trade. This was considered beyond our scope but, overall, may lower the future impact estimates if substantive substitution is possible.

We assume the commercially viable harvest window starts at age 80 years. Harvest costs were set to $\$20 \cdot \text{m}^{-3}$, postharvest treatment costs to $\$400 \cdot \text{ha}^{-1}$ (which is a basic silviculture scenario used in the Ontario Ministry of Natural Resources primary forest management planning model — SFMM (Davis 1999)), and the timber price at the mill gate to $\$35 \cdot \text{m}^{-3}$ (Peter and Nelson 2005). We used a 4% real discount rate, which is commonly used for longer-term forest investments (Row et al. 1981). Note that the discount rate choice remains a matter of debate in the economic literature (Portney and Weyant 1999). Higher rates will generally decrease net present values by decreasing the present value of future impacts. The converse is true for lower discount rates.

Scenarios

Our assessment of potential impacts is drawn from two basic scenarios — harvests with and without *S. noctilio*. The “business-as-usual” (BAU) scenario represents harvest-

Fig. 5. Total spread area over time for three different harvest scenarios (H1, H2, H3). p_0 is the local colonization probability, and V_{max} is the upper limit of pine mortality (cubic metres per hectare per year).



ing the current AAC in the absence of *S. noctilio*. We simulate harvesting the AAC with the *S. noctilio* invasion starting from southeastern Ontario (where it is currently known to exist). The spreading *S. noctilio* population kills pines and changes the V_{pine} , k_{host} , and PV_{timb} values and hence changes harvest decisions. The net impact is calculated as a difference between the “invasion” and BAU scenarios (Fig. 4).

We explore three basic harvest strategies, H1, H2, and H3 (Table 2), as possible large-scale responses to the invasion. The “no adaptation” scenario (H1) applies the same exact harvest configuration as the BAU runs and hence simulates the economic impacts without any alterations of harvest patterns. This scenario represents zero flexibility (no substitution possibilities) in harvest scheduling. The “value adaptation” scenario (H2) adapts the harvest in response to the invasion by allowing the harvest allocations to be driven by scoring model values. The “value + salvage” scenario (H3) also is driven by scoring model values, but moves the

harvest closer to infested areas and away from more productive sites, hence abandoning potentially more productive harvest choices (Table 2). H3 attempts to represent a situation of salvaging timber supply doomed to damage and is a more proactive removal of pine sources. Cost savings from adaptation policies can be found by comparing H2 and H3 with the no adaptation scenario H1, and the total economic losses from invasion, by comparing H1, H2, and H3 with the BAU scenario.

Results

Total impacts

Sirex noctilio is a new species to North America with a short detection history. These circumstances dictated the use of a relatively simple spread model and of a broad range of biophysical assumptions. Hence the results are expressed as “what-if” scenarios, which are arguably more appropriate than representations that infer definitive knowledge about either the biology of the species or the economics of management responses. We show the range of “what-if” results using four sets of spread assumptions: two V_{max} values (0.8 and 3.0) and two p_0 values (0.2 and 0.8), which represent quite a wide range of pine mortality and colonization potential.

The annual area of expansion by *S. noctilio* is close to linear after passing the establishment period. The scenarios with $p_0 = 0.8$ show mean rate of expansion values of 44.0 and 49.2 km·year⁻¹, and when $p_0 = 0.2$, the rate is between 39.0 and 45.0 km·year⁻¹. Because expansion events were not recorded outside of the study area, the mean rate of expansion shows a slight decline after the invasion approaches the study area boundaries. This effect usually occurs when at least 0.6%–1% of newly infected cells reach a 100 km zone near edge of the study area. The spread area shows a better response to the spatial distribution and the connectivity of host resources and hence may be a more useful metric.

The results do not show major differences in the spread area over time between the no adaptation (H1) and harvest reallocation scenarios (H2 and H3) (Fig. 5). However, the volume of pine mortality varies considerably (Table 3) and depends on V_{max} assumptions (higher V_{max} values mean more severe impact on pines). For example, the total killed volume over 20 and 28 years is 25.8×10^6 to 43.7×10^6 and 79.0×10^6 to 117.0×10^6 m³, respectively, where $V_{max} = 0.8$, and is 59.6×10^6 to 115.1×10^6 and 221.4×10^6 to 324.0×10^6 m³, respectively, where $V_{max} = 3.0$. The $V_{max} = 3.0$ scenario shows 2.2–3.1 times more volume of pine mortality compared with $V_{max} = 0.8$. The impact of p_0 values is also noticeable: mean volumes of killed pines are 1.9–2.2 times higher in the scenarios using $p_0 = 0.8$ than in the scenarios using $p_0 = 0.2$. In Quebec, the adaptation scenarios H2 and H3 with the low-infestation assumptions ($V_{max} = 0.8$ and $p_0 = 0.2$) show considerably lower amounts of killed volume until an abrupt increase after 24 years. This jump indicates the outbreak entering major pine regions in Quebec with the *S. noctilio* population reaching a carrying capacity on a majority of infested sites.

The choice of harvest allocation policy shows almost no impact on pine mortality (Table 3). Ontario shows the highest and the most immediate losses (97%, 78%, and 65% of total killed volume over 8, 20, and 28 years), and Quebec

Table 3. Volume of killed pine (millions of cubic metres) by province.

Year	$V_{\max} = 0.8$								$V_{\max} = 3$							
	$p_0 = 0.2$				$p_0 = 0.8$				$p_0 = 0.2$				$p_0 = 0.8$			
	Total	ON	QC	NBNS	Total	ON	QC	NBNS	Total	ON	QC	NBNS	Total	ON	QC	NBNS
No adaptation scenarios — H1																
4	0.01	0.01	—	—	0.03	0.03	—	—	0.01	0.01	—	—	0.03	0.03	—	—
8	0.29	0.3	0.01	—	0.86	0.8	0.04	—	0.38	0.4	0.01	—	1.14	1.1	0.04	—
12	2.4	2.3	0.1	—	5.7	5.1	0.6	—	4.4	4.3	0.2	—	10.8	10.0	0.8	—
16	10.3	9.1	1.1	—	19.3	15.7	3.7	—	21.7	20.1	1.6	—	43.6	37.2	6.3	—
20	25.8	21.5	4.3	—	43.3	31.5	11.8	—	64.8	56.0	8.8	—	111.5	85.6	26.0	—
24	49.5	37.7	11.7	—	74.8	50.2	24.6	<0.01	136.4	107.2	29.2	<0.01	208.6	145.1	63.6	0.01
28	79.7	56.4	23.4	—	111.5	71.9	39.6	0.1	230.7	165.8	64.9	<0.01	319.1	208.7	110.2	0.2
Maximize PV(net timber returns) — H2																
4	0.01	0.01	—	—	0.03	0.03	—	—	0.01	0.01	—	—	0.03	0.03	—	—
8	0.29	0.3	0.01	—	0.87	0.8	0.04	—	0.38	0.4	0.01	—	1.16	1.1	0.04	—
12	2.4	2.3	0.1	—	5.7	5.1	0.7	—	4.43	4.3	0.2	—	11.1	10.2	0.9	—
16	9.6	8.5	1.1	—	19.6	15.7	3.8	—	21.65	19.8	1.9	—	45.7	39.3	6.4	—
20	24.9	20.4	4.5	—	43.7	31.5	12.2	—	64.4	54.7	9.7	—	115.0	89.3	25.7	<0.01
24	48.5	36.2	12.3	—	75.2	50.1	25.1	0.01	136.5	105.2	31.3	<0.01	212.5	149.9	62.7	0.01
28	78.6	54.3	24.2	<0.01	111.7	71.5	40.0	0.22	231.3	163.2	68.1	<0.01	323.9	214.6	109.1	0.3
Allocate harvests closer to infested locations — H3																
4	0.01	0.01	—	—	0.03	0.03	—	—	0.01	0.01	—	—	0.03	0.03	—	—
8	0.28	0.3	0.01	—	0.85	0.8	0.04	—	0.36	0.4	0.01	—	1.14	1.1	0.04	—
12	2.3	2.2	0.1	—	5.4	4.8	0.60	—	4.1	4.0	0.1	—	11.0	10.2	0.8	—
16	9.6	8.1	1.5	—	18.4	14.9	3.6	—	19.9	18.3	1.6	—	45.7	39.7	6.0	—
20	28.0	19.8	8.3	—	41.7	30.0	11.7	—	59.6	51.3	8.3	—	115.1	89.8	25.3	—
24	63.5	35.3	28.2	—	72.3	48.0	24.3	<0.01	128.6	100.4	28.2	<0.01	212.9	150.2	62.7	<0.01
28	117.0	53.2	63.8	<0.01	107.4	68.2	39.1	0.1	221.4	157.6	63.8	<0.01	323.6	214.2	109.3	0.11

Note: p_0 is the local colonization probability, and V_{\max} is the upper limit of pine mortality (cubic metres per hectare per year). ON, Ontario; QC, Quebec; NBNS, New Brunswick and Nova Scotia; PV, present value.

bears most of the remaining losses (3%, 22%, and 34%, Table 3). While invasion reaches the Maritime Provinces in less than 18 years, the impact on pine volume is very small in the short term (Table 3) with these spread assumptions. Note that this analysis does not assume additional *S. noctilio* entries from the continental United States.

Direct losses

Table 4 shows net present values, and Table 5 shows the undiscounted annual cash flows of harvest losses (both metrics are shown as the difference between invasion and BAU scenarios). Direct economic losses (Table 4) show less variation than do volumes of pine mortality (Table 3). There is almost no dependence on V_{\max} . For example, annual cash flow losses after 20 years of invasion were \$87 to \$254 million and \$86 to \$249 million per year for the scenarios using $V_{\max} = 0.8$ and 3.0, respectively (Table 5).

The impact of p_0 values is more noticeable. Annual cash flow losses after 20 years are \$111 to \$254 million and \$86 to \$215 million per year in the $p_0 = 0.8$ and $p_0 = 0.2$ scenarios, respectively. Scenarios using $p_0 = 0.8$ have 1.1–1.9 times higher annual losses than scenarios using $p_0 = 0.2$.

The choice of harvest policies has the largest economic impact (Table 4). Annual losses in the harvest-adaptation scenarios where economic present value was maximized (H2) are 1.7–2.5 times lower than those in the no adaptation scenario (H1). For example, H2 shows annual losses between \$86 and \$113 million per year at year 20, while H1 shows losses of \$212 to \$254 million per year.

In most scenarios economic losses are split mostly be-

tween Ontario and Quebec. Losses in the Maritimes start to grow only after 24 years of invasion by *S. noctilio*. The scenario where present value is maximized and harvests are allocated closer to the infested locations (H3) shows economic costs in Maritimes starting early in the simulation, because of increased transportation costs (Table 5).

Total losses show a similar tendency and linearly increase with time (Table 5). Depending on the harvest policy, the total net present value over 28 years is within \$1.5 to \$2.1 billion in H1, \$0.7 to \$1.1 billion in H2, and \$1.2 to \$1.9 billion in H3. Total lump-sum savings from using harvest adjustments reach \$0.84 to \$1.0 billion over 28 years (Table 4).

Effect of harvest policies

Figure 6 shows the time dynamics of harvests in infested stands (infestations older than 5 years). In the no adaptation scenarios (H1), harvests from infested stands increase proportionally to the area invaded and time. After the invasion covers most of an AAC region, harvests in infested stands reach a plateau, thus indicating the beginning of large-scale timber supply shortages and failures to sustain the AAC (Fig. 6, AAC(H1) lines).

In the H2 and H3 adaptation scenarios, harvests from infested sites are used as a “last resort” to sustain the AAC and usually just precede larger-scale timber supply shortages. Figure 6 also shows the beginning of the large-scale failures to sustain the AAC objective after 19–24 years in the H1 scenario (the declining portions of the AAC(H1) lines). The H2 and H3 scenarios (Fig. 6, AAC(H2,H3)

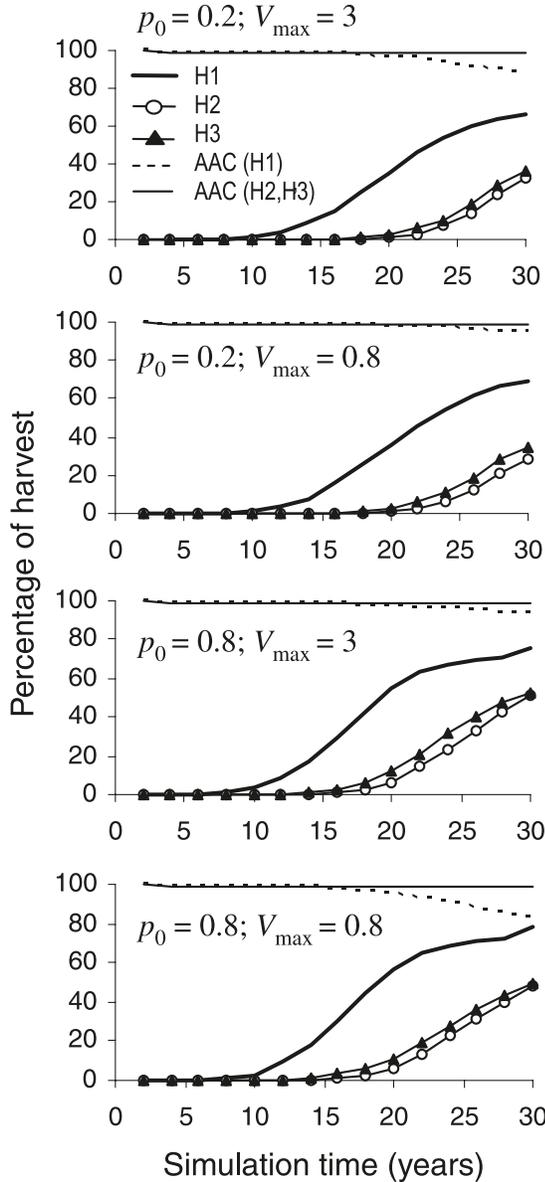
Table 4. Total cumulative lump-sum economic losses (net present value) from *Sirex noctilio* (millions of dollars).

Year	$V_{\max} = 3$															
	$p_0 = 0.2$						$p_0 = 0.8$									
	Total	ON	QC	NBNS	Total	ON	QC	NBNS	Total	ON	QC	NBNS				
No adaptation scenarios — H1																
4	1.6	1.5	0.2	—	6.7	5.9	0.8	—	1.6	1.5	0.13	—	7.7	6.6	1.1	—
8	38	29	9.2	—	101	70	31	—	36	26	9.5	—	100	69	31	—
12	183	136	47	—	373	247	126	—	174	126	48	—	367	236	131	—
16	455	318	138	—	811	478	334	—	448	298	151	—	803	461	343	—
20	822	521	301	—	1289	714	575	—	815	492	324	—	1273	690	584	—
24	1212	722	491	—	1724	934	788	2.2	1196	681	515	—	1692	897	790	5.4
28	1568	904	664	—	2147	1161	967	20	1535	853	682	—	2086	1103	956	27
Maximize PV(net timber returns) — H2																
4	5.2	3.3	1.8	0.1	9.6	7.0	2.6	0.1	5.6	3.8	1.8	0.04	8.8	6.3	2.4	0.1
8	28.2	19	8.7	0.6	73	50	23	0.3	27	18	9.3	0.3	72	50	22	0.5
12	98	72	25	0.4	220	146	75	0.4	97	70	27	0.5	225	150	75	0.5
16	220	151	69	0.5	433	251	182	0.5	223	149	74	0.7	442	257	184	0.6
20	371	229	143	0.4	636	346	290	0.6	377	225	151	0.8	646	352	293	0.7
24	530	306	224	0.4	856	450	402	4.3	535	299	236	0.8	864	454	405	5.0
28	698	390	308	0.5	1134	594	525	15	699	377	321	1.0	1118	577	524	16
Allocate harvests closer to infested locations — H3																
4	139	74	52	14*	159	86	58	15	140	76	52	14	158	85	58	15
8	281	142	104	34	360	188	137	35	277	141	104	32	370	198	136	37
12	442	235	153	53	621	336	230	55	436	232	153	51	634	352	228	55
16	622	347	204	70	898	481	344	74	613	342	204	67	908	492	344	73
20	824	457	284	83	1189	618	480	92	810	447	284	79	1206	634	483	89
24	1048	571	383	93	1514	774	633	106	1027	555	383	89	1535	797	638	100
28	1298	695	500	103	1860	956	786	118	1274	677	500	98	1876	978	787	111

Note: Values above 10 are rounded to a nearest integer. p_0 is the local colonization probability, and V_{\max} is the upper limit of pine mortality (cubic metres per hectare per year). ON, Ontario; QC, Quebec; NBNS, New Brunswick and Nova Scotia; PV, present value.

*Above-zero values for NBNS in H3 scenarios are a result of harvest reallocations.

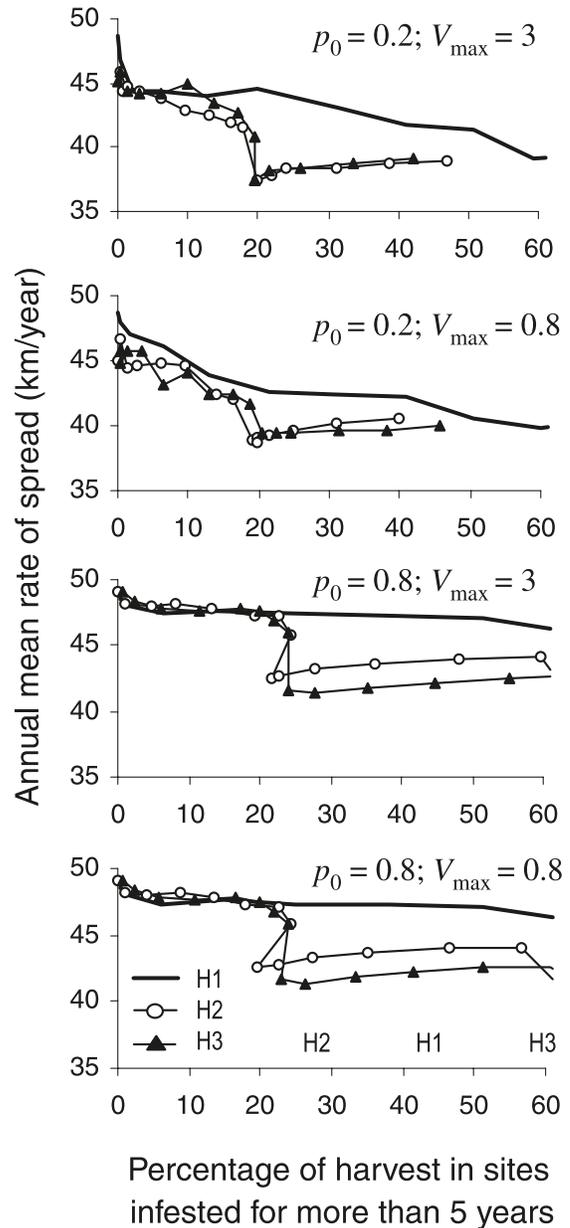
Fig. 6. Total harvest as a percentage of the annual allowable cut (AAC) objective (%), and the proportion of harvest from forest sites with *Sirex noctilio* (%), ≥ 5 -year-old infestations). AAC(H1) and AAC(H2,H3) lines show the total harvest as a percentage of the AAC objective in the H1, H2, and H3 scenarios. p_0 is the local colonization probability, and V_{max} is the upper limit of pine mortality (cubic metres per hectare per year).



lines), however, show that adaptation policies help delay large-scale impacts on harvests by at least 9–11 years. Abrupt increases in harvests in infested areas also have very small but consistent effects on the rate of spread. Figure 7 shows annual mean rate of spread as a function of harvest proportion from infested sites. Both adaptation scenarios (H2 and H3) show that mean rate of spread declines slightly when harvest from infested sites exceeds 20%–25% of its AAC limit.

We show that the H3 scenario illustrates a more preventive adaptation policy that moves harvests closer to infested areas. Compared with H2, H3 shows similar results on the

Fig. 7. Rate of spread versus the amount of harvest from the forest sites with *Sirex noctilio* (≥ 5 -year-old infestations). p_0 is the local colonization probability, and V_{max} is the upper limit of pine mortality (cubic metres per hectare per year).



rate and area of spread (Figs. 5 and 7) and killed volume (Table 3). However, the scenario also shows higher short-term economic losses as a result of increased transportation costs and the obligation to harvest less-productive stands near infested areas. Interestingly, during the first 10–12 years, cash-flow losses also exceeded those in the no adaptation scenario (H1).

Discussion

The actual impact of *S. noctilio* on harvest values will be driven by complex interactions among insect spread, tree mortality, and harvest adaptations. In our simulations, economic losses vary significantly between scenarios, so

clearly, personal perspectives about the assumptions will affect perceptions about possible risks. In a sense these losses can be divided into two components. The first component is the direct costs of adapting harvest policies in response to invasion when the harvest can still sustain the AAC target. In the short term, these costs do not necessarily correlate with the rate of pine volume reduction. Over time, however, the invasion depletes the regional timber supply to a point when it is no longer possible to achieve the AAC. Thus a second component marks the failure to sustain the current AAC and quantifies more advanced stages of a *S. noctilio* invasion with large-scale timber supply shortages. To better quantify this component would require a greater understanding of *S. noctilio* long-term population dynamics and more details on AAC determinations. Our results nevertheless provide some general indications about this component. Most of the no adaptation scenarios start failing to maintain AAC after 20 years or longer (depending on the severity of infestation, Fig. 6) and when the infested area exceeds approximately 15×10^6 ha (Fig. 5). This period suggests a possible time frame to generate management responses and control programs. However, we do not consider potential cost savings from harvesting alternative species or a cross-provincial harvest substitution. To do this well would require more detailed knowledge on mill capacities and is beyond our current objectives or capabilities.

We did not find a specific threshold of timber lost that triggers large-scale failures to sustain the AAC objective. No adaptation scenarios show this threshold between 43×10^6 and 111×10^6 m³ of pine mortality over 20 years. Harvest-adjustment scenarios (H2 and H3) usually show higher levels starting from 230×10^6 m³.

Our basic representation of harvest planning heuristics helps represent adaptation strategies that are widely used in forest harvest planning. Despite the negligible impact on the rate of spread, harvest-adaptation policies do appear to help reduce short-term losses from invasion by 46%–55%. In general, harvest reallocations tend to avoid heavily infested sites with declining quality of standing timber. The results also suggest that a preventive practice of moving the harvest closer to an infested area may not reduce costs. This preventive practice also does not reduce the physical losses of pine volume from the *S. noctilio* infestation. Existing AAC limits are simply too small to create a quarantine harvest corridor comparable with the known dispersal range of *S. noctilio*. Recent experience with mountain pine beetle also suggests that such a policy may only work in conjunction with a rapid AAC increase (British Columbia Ministry of Forests 2005) or may only work for slow-spreading infestations. Ironically, existing AAC policies may severely limit managers' flexibility to adapt harvest policies in response to catastrophic pest invasions. Theoretically, it is possible to generate scenarios that modify the AAC objectives in an attempt to minimize the losses from the infestation. This issue is complex and very dependent on specific provincial forest management policies.

Improving forest stand conditions can be an effective policy that could reduce the susceptibility of pine stands to *S. noctilio* attacks. While the current model can be modified to recreate these policies, the lack of high-resolution spatial information on stand conditions precludes the large-scale

model applications of such policies. Our estimates do not incorporate impacts on other nontimber values such as changes in recreation opportunities or losses in a carbon sequestration potential arising from a large-scale *S. noctilio* infestation. While tracking carbon sequestration benefits is within CFS-FBM capacity, the accounting rules for temporary carbon offsets from forestry are not yet finalized in Canada and would strongly influence the results. The issue of CO₂ emissions from disturbances may also be subjected to provincial regulations and will require further research efforts.

Our choice of a fixed timber price clearly affects the aggregate outcome. Fixed changes in timber prices would affect the undiscounted cash flows linearly, while a more complex timber price representation is more difficult to predict. Other price fluctuations and feedbacks from market adaptations represent another aspect not yet addressed in this work that could obviously affect the NPVs. Practical implementation of this idea may require major analytical and methodological efforts such as formulating price fluctuation hypotheses from historic trade statistics data and linking the price processes to ever larger-scale harvest planning levels.

Conclusions

Alien invasive species are one of the most serious economic threats in North America. While general projections of estimated annual losses from exotic invasions do exist (e.g., Pimentel et al. 2000, 2005), they do little to help local decision makers (Toman 1998). Assessments focused on particular invasive species and their more direct economic impacts are believed to be more valuable for resource managers, as these can be better linked to adaptation, including regulatory policies and tactical actions (Cook and Proctor 2007). This modeling study focuses on a new recently discovered pest, *S. noctilio*, and uses an integrated bioeconomic model to generate the projections of possible *S. noctilio* spread and direct impacts on pine wood supply and harvest.

For *S. noctilio*, it appears that some harvest-adaptation policies could reduce costs and could help buy some time (at least 9–11 years) before its invasion sets off larger-scale timber supply shortages (cost savings in this particular simulation could reach 45%–56%). Thus the results also support existing evidence that outbreak impacts can be mitigated somewhat (Hall et al. 1993). This time period is also a general indicator or target for pest management solutions should *S. noctilio* prove to be as devastating as these models suggest. The results suggest that, given quite broad-ranging assumptions about *S. noctilio*, large-scale timber supply shortages may not be preventable by adapting harvests and therefore will require a successful silvicultural and (or) biological control program of *S. noctilio*. Harvest policies that focus on salvage may not be attractive because of increased transportation costs and a long flying range of an invader. This agrees with previous experience with *S. noctilio* in Australian conditions (Haugen et al. 1990) and existing adaptation practices in other regions threatened by large-scale outbreaks such as mountain pine beetle epidemics in British Columbia (British Columbia Ministry of Forests 2006). Finally we suggest that more localized modeling of the ecology of *S. noctilio*, trophic-level interactions, and impacts be undertaken to improve our estimates and reduce the

uncertainty of spread predictions, since much of our understanding of *S. noctilio* is based on data from areas where it is an invasive pest attacking exotic pines.

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