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A harvest failure approach to assess the threat from an invasive species

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ABSTRACT

We present the idea of using potential infringements on annual allowable harvest targets as an approach to estimate threats from invasive species to the forest products sector. The approach uses present-day harvest levels as a reference level to estimate when and where the impact of a nonnative forest pest could become economically damaging. We use a generic model that simulates spread and damage by nonnative invasive species, basic harvest and forest growth through time. The concept is illustrated with a case study of a new nonnative invasive pest, *Sirex noctilio* Fabricius on pine resources in eastern Canada. Impacts of invasion on wood supply, in particular, the point at which present-day harvest levels are not attainable, were identified for 77 non-overlapping geographical regions that delimit the primary wood supply areas around large mills and wood processing facilities in eastern Canada. The results identify the minimum area of a pest outbreak that could trigger harvest shortages (approximately 12.5–14 M ha of pine forests in Ontario and Quebec). Beyond this level, the amount of host resource available for harvesting in any given year declines rapidly. The failure to sustain broad-scale harvest targets may be an attractive and intuitive indicator for policy makers and regulators interested in developing control and "slow-the-spread" programs for non-native forest pests.

1. Introduction

Understanding the possible threats and impacts of a nonnative invasive species requires knowledge of its spread potential and physical consequences. While some situations allow the physical impacts of an invasion to be estimated with reasonable accuracy (Cook et al., 2007; Leung et al., 2005; Van Leeuwen et al., 2001), assessments are often limited to generalized, non-spatial estimates (Pimentel et al., 2000, 2005) that do little to address specific environmental impacts, costs, timelines or mitigation options (Toman, 1998). However, it is precisely this type of more detailed information that is requested by decisions makers when determining a course of action in response to a species invasion (Keller et al., 2007).

Assessing the potential environmental and economic impacts of any new invasive species is extremely challenging given various knowledge gaps around their behavior and biophysical and economic impacts. Often, when very little is known about a new invader, an impact assessment may simply identify the gross potential physical amount of susceptible host resource under threat and multiply this quantity by a unit price (Borchert et al., 2007). While this approach is simple and transparent and may help to quickly estimate a potential maximum impact, it ignores the time dynamics of the process and hence does not address important issues such as when and where invasion-induced damages might occur. As a result, these 'ballpark' estimates often draw skepticism from decision-makers and land managers.

In Canada, the annual amount of forest wood supply that can be harvested in a landscape without diminishing the biological sustainability of the region is identified by the Annual Allowable Cut (AAC). Essentially, the AAC is a regulatory limit calculated by Provincial land management agencies (e.g., OMNR, 1996). The annual allowable cut concept is well recognized in forestry (Buongiorno and Gilless, 2003; Vanclay, 1996a,b) and can be

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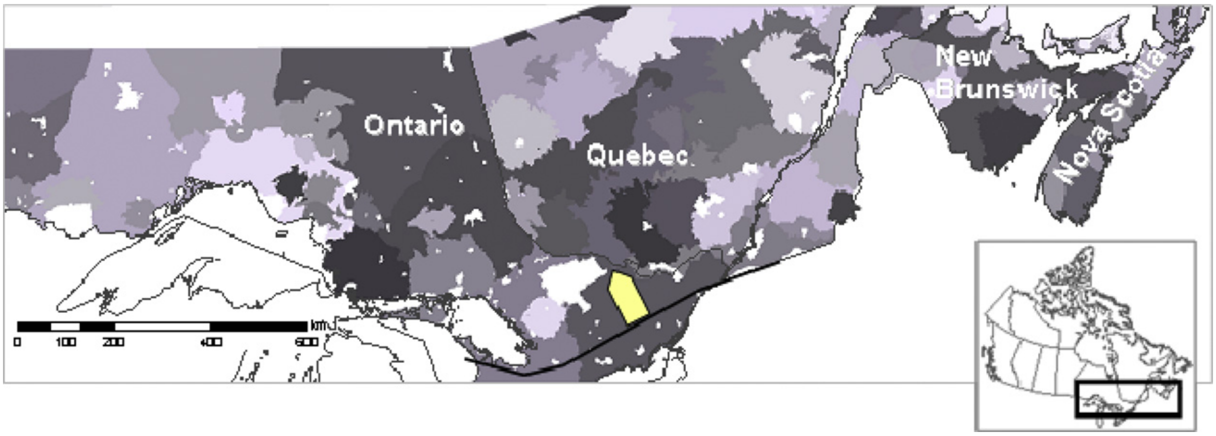

Fig. 1. Map of Forest Management Regions (FMRs) in eastern Canada. Bold line shows the initial *S. noctilio* infestation. Arrow shows the direction of invasion spread.

described as the harvest that can be taken each and every year of an *n*-year harvesting cycle, so that the resource is harvested in exactly *n* years without endangering the sustainability of the forest resources (Vanclay et al., 2006). The concept is widely adopted and embedded in natural resources management polices in Canada (OMNR, 1996), U.S. (Hrubes, 1976; Buongiorno and Gilless, 2003), Australia (Vanclay, 1996a,b) and other major wood producing countries (e.g., Howard, 2001; Mutanen et al., 2005; Haase and Camphausen, 2007). Actual harvest volumes will ultimately be driven by market forces and socio-economic considerations and may not always reach AAC targets in any given year. Nevertheless, it seems reasonable the present-day harvest levels constrained by AAC should be taken into account when estimating risks from nonnative pest outbreaks.

The invasion of an exotic pest causes the mortality of commercial tree species and a decline in their productivity. In the early phases of an invasion, this decline can be compensated for by regeneration and growth in other species or could be minimized via adaptation of forest management and/or harvest policies. In fact, one study suggests that historical outbreaks of jack pine budworm (*Choristoneura pinus* Freeman) have not led to shortages in the regional wood supply as a result of adaptation of management practices (Conway et al., 1999). Nevertheless, adaptations of present-day management practices may not be sufficient in the case of a nonnative species outbreak that spreads quickly and causes severe damage. In such a case, the outbreak may initiate a cascade of consequences, including: wood supply reductions, regulations on wood movement, mill closures, and an overall decline in forest land values (as illustrated by an ongoing mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in British Columbia (BCMOF, 2005, 2007; Patriquin et al., 2007; Phillips et al., 2007)). Thus the "business-as-usual" harvest levels can be used as a reference point in estimating future impacts of invasive forest pests. In particular, the point when the present-day harvest levels (AAC) may become unattainable can be interpreted as an important forest-sector impact metric for alien species invasions (henceforth referred to as a "harvest failure threshold").

Here we present a case study that illustrates the harvest threshold concept to assess possible impacts from an exotic forest pest at a broad spatial scale. We employ a simulation model that projects three basic components of invasion over time: (1) a geographical distribution of forest resources and their growth over time, (2) the spread of the invasive pest and its impact on the susceptible host through time, and (3) a geographic representation of this impact on broad-scale wood harvests through time. We use the spatial model described in Yemshanov et al. (2009a) to simulate present-day regional harvest activities and identify when and where these harvest levels may be compromised given a particular invasion scenario. Such information could be useful for developing regional mitigation and regulatory strategies in response to new invasive species and thus better target their implementation.

This study focuses on a relatively new invasive threat, *Sirex noctilio* Fabricius, a pine woodwasp which was first detected in the United States in 2004 and in Canada in 2005 and is now spreading across eastern North America (de Groot et al., 2006; Hoebeke et al., 2005). It is considered a major damaging pest of introduced pine plantations in the Southern Hemisphere (Bedding, 2009; Corley et al., 2007; Haugen, 2006; Haugen and Underdown, 1990; Hurley et al., 2007). As of December 2008, the woodwasp has been found in Michigan, New York, Pennsylvania and Vermont (US) and in Ontario and Quebec (APHIS, 2008; NAPPO, 2008). An introduced pine *Pinus sylvestris* L. appears to be the prime target, but native pine species (*P. resinosa* Ait. and *P. banksiana* Lamb.) have also been attacked (FHTET, 2007; Haugen and Hoebeke, 2005). *S. noctilio* has a broad bioclimatic distribution (Carnegie et al., 2006) and could potentially colonize the entire range of industrial forestry in eastern Canada.

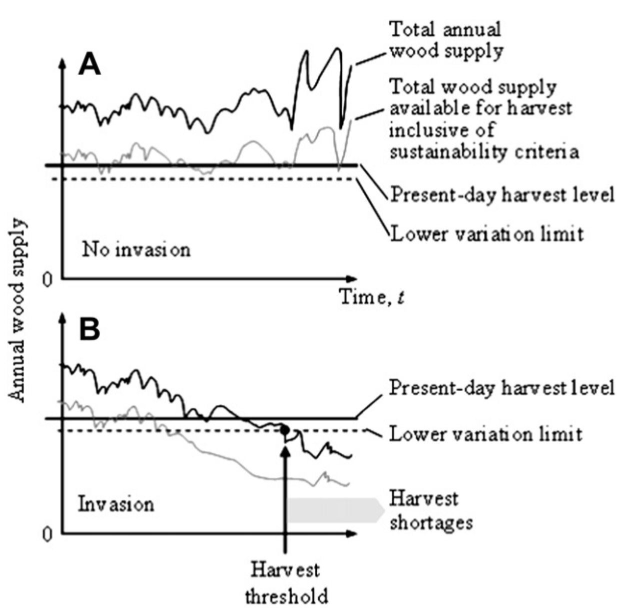

Fig. 2. A schematic of the harvest failure threshold concept. A – no invasion; B – invasion scenario.

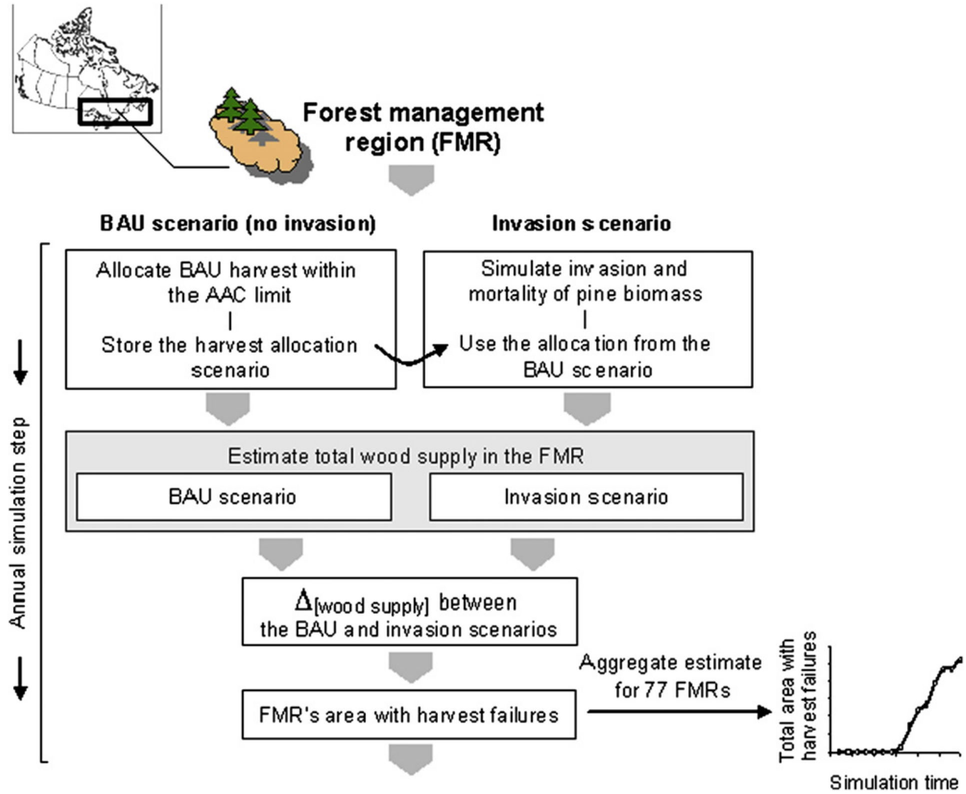

Fig. 3. Summary of the harvest failure analysis.

2. Methods

2.1. Modeling approach

We use the spatial Canadian Forest Service Forest Bioeconomic Model (CFS-FBM) as a platform to combine the required biophysical and economic analyses. The basic concept is described in Yemshanov et al. (2007) and modifications for invasive species scenarios in Yemshanov et al. (2009a,b) and Koch et al. (2009). Here we provide only the details germane to the present study.

We adopt the traveling wave model of Sharov and Liebhold (1998) to simulate spread as a discrete two-dimensional colonization process at the meta-population level, For any spatial location, the colonization rate is calculated as a function $f(x)$ of distance from the nearest infected location constrained by the maximum distance at which *S. noctilio* populations may become established at any given year, x_{max} (Yemshanov et al., 2009a). The shape of $f(x)$, the local colonization probability, p_0 and the maximum annual spread distance, x_{max} were based on observations from the Southern Hemisphere (Carnegie et al., 2006; Haugen et al., 1990) and estimated $x_{max} \approx 50$ km and p_0 ranging from 0.2 to 0.8. These estimates are based on discussions with various scientists and on published and unpublished studies of historical spread and impact. Other critical model assumptions included the geometric growth rate, maximum carrying capacity of Sirex population (following Sharov and Liebhold, 1998), the growth rates, susceptibility, geographic distribution and the timeline of host species decline (see details in Yemshanov et al., 2009a). The model was initialized with the map of positive *S. noctilio* detections based on 2006 CFS-CFIA surveys and tracks established metapopulations of a minimum size equal to the map resolution (400 m).

We also estimated the maximum annual rate of pine mortality, V_{max} that essentially limits the maximum annual damage rate of a commercial wood supply. The value of V_{max} was calculated from the rate of pine mortality based on previous experiences in the Southern Hemisphere where, given a typical stem size distribution, massive outbreaks could potentially destroy up to 80% of a pine stand over a period of 15 years. Based on expert estimates, we defined two alternative values of V_{max} (i.e., 0.8 and 3.0 m^3/ha/year) for a typical diameter distribution and species composition in eastern Canada (see Yemshanov et al. (2009a)), and growth rate assumptions in unmanaged boreal pine stands in Canada. While V_{max} sets an average upper pine mortality limit, actual mortality at individual forest sites is also limited by the amount of standing pine volume and the time since infestation.

2.2. Harvest

Here we consider wood harvests as the primary economic use of the susceptible host (pine forests). Our representation of harvest activities is implemented to provide a broader-scale perspective on forest management regions (FMRs) and is not intended to mimic operational planning or detailed optimization-based industrial wood supply allocations. Note that the designated regions represent the bulk of the wood supply for major mills and industrial wood users, not forest management planning boundaries used by Provincial ministries and forest companies (Fig. 1, explained in more detail below).

Since our intention was to use general harvest levels only as a reference point in a broad-scale pest risk assessment, our preference here was to use simple heuristic allocation methods (Bettinger et al., 2002). This approach is also better at dealing with the assumptions and processes represented in stochastic or probabilistic models (for example here the geographical distribution of damages to pine biomass, the spread of invasion and also generalized harvest criteria). We used a simple scoring method with two criteria: the present value of timber revenues net of harvest, transportation and mandatory regeneration costs, PV_{host}, and

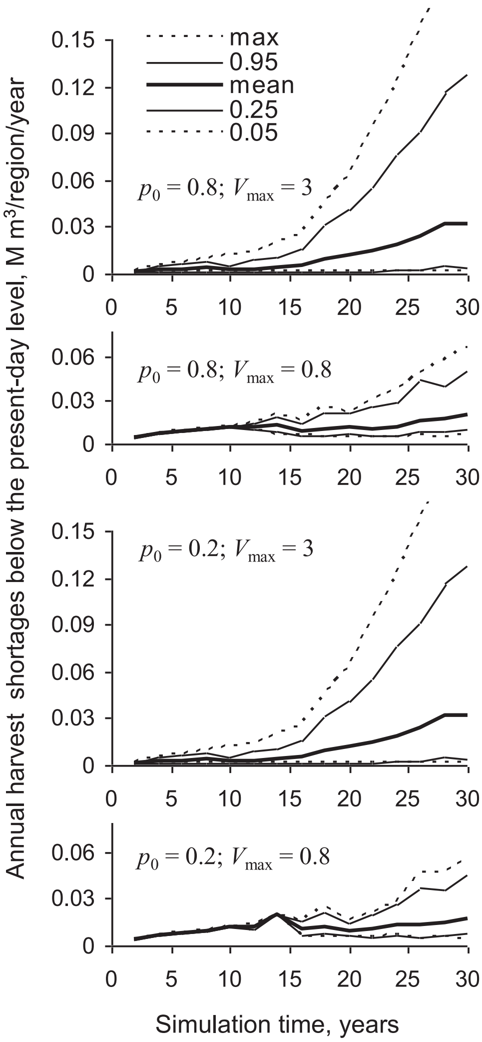

Fig. 4. Variation across Forest Management Regions in harvest shortages ($\times 10^6$ m^3/region/year). p_0 is the probability of colonizing the nearest spatial location; V_{max} is the maximum expected annual rate of pine mortality (m^3/ha/year).

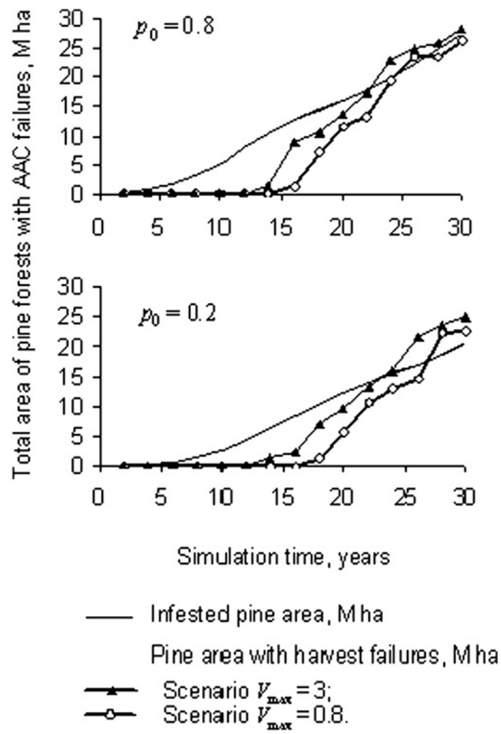

Fig. 5. Area of pine forests with expected harvest shortages (M ha). p_0 is the probability of colonizing the nearest spatial location; V_{max} is the maximum expected annual rate of pine mortality (m^3/ha/year).

a spatially uniform random error, σ that represents other harvest considerations:

$$X_i = \sigma \cdot k_\sigma + k_h \cdot \mathrm{PV}_{host} \quad (1)$$

where k_σ and k_h are weighting coefficients. k_σ is set to 0.2 and k_h to 0.8. The PV_{host} was calculated as the sum of present values of individual harvest blocks over a planning horizon, T:

$$\mathrm{PV}_{host} = \sum_{i=0}^{M_t}\left[\sum_{t=0}^{T}\left[\frac{V_{host_i}\cdot[p_w\cdot(1-k_{host_i})-c_{hrv_i}]+V_{other_i}\cdot([p_w-c_{hrv_i}]-c_{regen})}{(1+r)^t}\right]\right] \quad (2)$$

where V_{host_i} and V_{other_i} are the annual per hectare volume of host and other species harvested at a given location, i, m^3/ha; p_w is the wood price ($35/m^3 mill gate value (Peter and Nelson, 2005)); k_{host} is the adjustment coefficient that is applied to a wood price if the invasive pest was found in a given area (0.75); c_{hrv_i} is the value of harvest and distance-dependent transportation costs ($/m^3); c_{regen} is the post-harvest treatment costs prescribed by Provincial guidelines ($400/ha); r is the risk-free interest rate (4%), and M_t is the total harvest area at a given year, t that is estimated from mills' wood supply requirements in the forest management regions and constrained by the regional AAC limit (see Yemshanov et al., 2009a for details).

As noted above, AAC determinations are usually done for forest management planning units or license areas (OMNR, 2004; Sougavinski and Doyon, 2005). Because real harvest volumes of harvests often fall below the provincial AAC limits, we calculated the harvest levels from known loads and capacities of existing mills and wood processing facilities. We believe the present-day harvests represent a better baseline for current use of forest resources and hence are relevant for assessing the future risks and impacts from invasive forest pests. In our study, mill consumption data was compiled for major softwood species. This included a search of publicly available data sources, provincial forest management documents, and communications with industry representatives. We aggregated neighboring mills or small wood processing facilities into larger units with total wood consumption volumes of 10^5 m^3/ha/year or greater.

We assumed that every group of mills would have a sufficient supply of pine in the surrounding area. A satellite-based SPOT-VGT land cover classification (Latifovic et al., 2004) was used to delineate areas of coniferous and mixedwood forests across eastern Canada. Annual mill consumption was used to calculate the total annual wood supply requirements. The model allocates wood

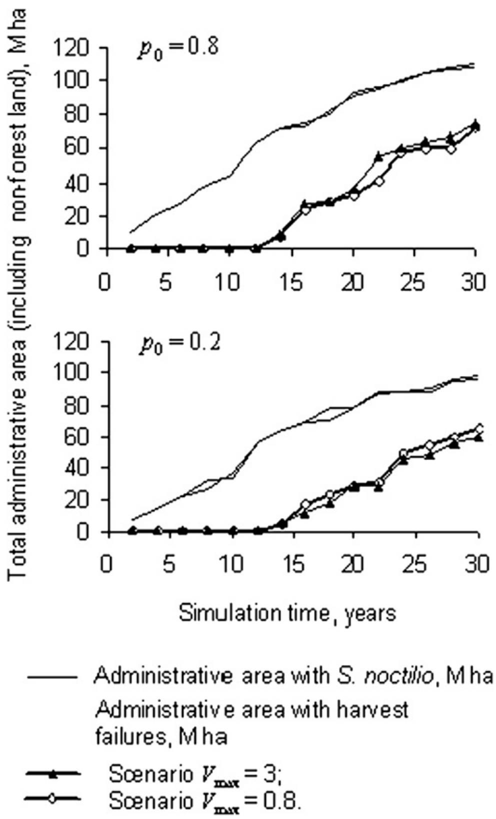

Fig. 6. Administrative area (including non-forest land) of expected harvest shortages (M ha). p_0 is the probability colonizing the nearest spatial location; V_{max} is the maximum expected annual rate of pine mortality (m^3/ha/year).

supply areas from locations closest to the mills and progresses in radial directions until reaching another FMR boundary. Here we used an average 100-year rotation and a growth rate of 1.9 m^3/ha/year based on the National Forest Inventory database (Gillis, 2001) (this somewhat low growth rate estimate includes potential losses due to natural disturbances). For each FMR, we also confirmed that present-day harvest levels could be sustained over at least one rotation (this was done via 100-year model runs without invasion from exotic pests). The pine portion of the AAC, was calculated as a ratio between pine and the total volume of conifer species in the FMR. The study area included 77 non-overlapping FMR's around each mill group with individual harvest limits for pine (Fig. 1).

2.3. Identifying the harvest failure threshold

Under normal circumstances, a forest landscape should have sufficient volume and growth of productive timber to sustain the AAC (Fig. 2A). In Canada AAC levels typically account for mortality caused by natural disturbances, biodiversity and conservation requirements and also other socio-economic considerations. When a new invasion occurs, the mortality of standing biomass gradually reduces the total amount of wood eligible for harvest over time (Fig. 2B). Eventually the wood supply becomes depleted to the point that harvesting the present-day volumes is no longer possible (Fig. 2B).

It is important to distinguish natural variations in age structure and biomass growth that may temporarily push wood supply and harvest levels below the present-day levels (Fig. 2A) from a persistent and gradual decline associated with an invasion (Fig. 2B). To do this, we simulated harvest allocations and volumes under the 'no-invasion' scenario. The reason for this threshold was not to emulate the impact of natural disturbances but rather to separate the invasion impact from the variations caused by other factors in the model (such as growth or age structure). In 95% of the model runs, the deviation of annual harvest volumes from the present-day target was 4020 m^3/year per region or less. Based on these findings, we set the model threshold that defines the onset of harvest decline to 4000 m^3/year/region below the present-day harvest levels.

2.4. Analysis

The analysis was completed in two steps (Fig. 3). First, we simulated a scenario with no invasion and a harvest allocation based on cost minimization strategies. The outputs provided the location of harvest sites and also the region-to-region variation of the annual harvest volumes around the present-day levels. This harvest configuration in the absence of invasion was stored and then compared to the invasion scenario. This essentially simulates zero-flexibility of harvest policies and hence eliminates the uncertainties that may be introduced by harvest adjustments, mitigation choices or manager's risk perceptions (which are often dictated by real-life economic considerations and do not follow optimization-based model forecasts – see discussion in Boyland et al., 2005). Here four infestation scenarios have been evaluated using the combination of *S. noctilio* spread model parameters, $V_{max} = 0.8$ and 3 m^3/ha/year and $p_0 = 0.2$ and 0.8 hence representing the current range of expert estimates about the extent and severity of the invasion. We provide aggregated area estimates and a geographical distribution of expected harvest failures across eastern Canada.

3. Results

The extent to which harvest volumes fell short of the present-day volumes varied considerably across the 77 FMRs (Fig. 4). Scenarios with the higher biomass mortality rate (i.e., $V_{max} = 3$) showed greater variation in harvest volumes across the FMRs. In all the scenarios, this variation increased considerably after 15 years, indicating the potential occurrence of harvest failures in Ontario and Quebec.

3.1. Area estimates of harvest failures

Estimates of pine forest area with expected harvest shortages are shown in Fig. 5. Note again, we use the threshold 4000 m^3/region/year, which distinguishes a systematic harvest decline caused by the invasion from the stochastic fluctuations in model outputs caused by other factors in the model. Most scenarios suggest the beginning of harvest shortages 14–18 years from the initial infestation or later. The dynamics of harvests over time shows a piecewise behavior with well-defined thresholds: the area of harvest shortages grew abruptly after the invasion spread over a significant portion of wood supply region (Fig. 5). For example, in 20 years, 6–13.7 M ha of pine forest may not be able to sustain harvest at the current-day harvest levels. Over 30 years, the area of harvest failures could potentially affect 23–28.4 M ha which represents ~62% of the total pine forest area in the study region. In all the scenarios, the area of harvest shortages suggests no decline for the first 16 years and then linear decline when the invasion covers most of the forest management area (approximately 8–10 M ha of pine forest in medium-infestation and 10–12 M ha in high-infestation scenarios).

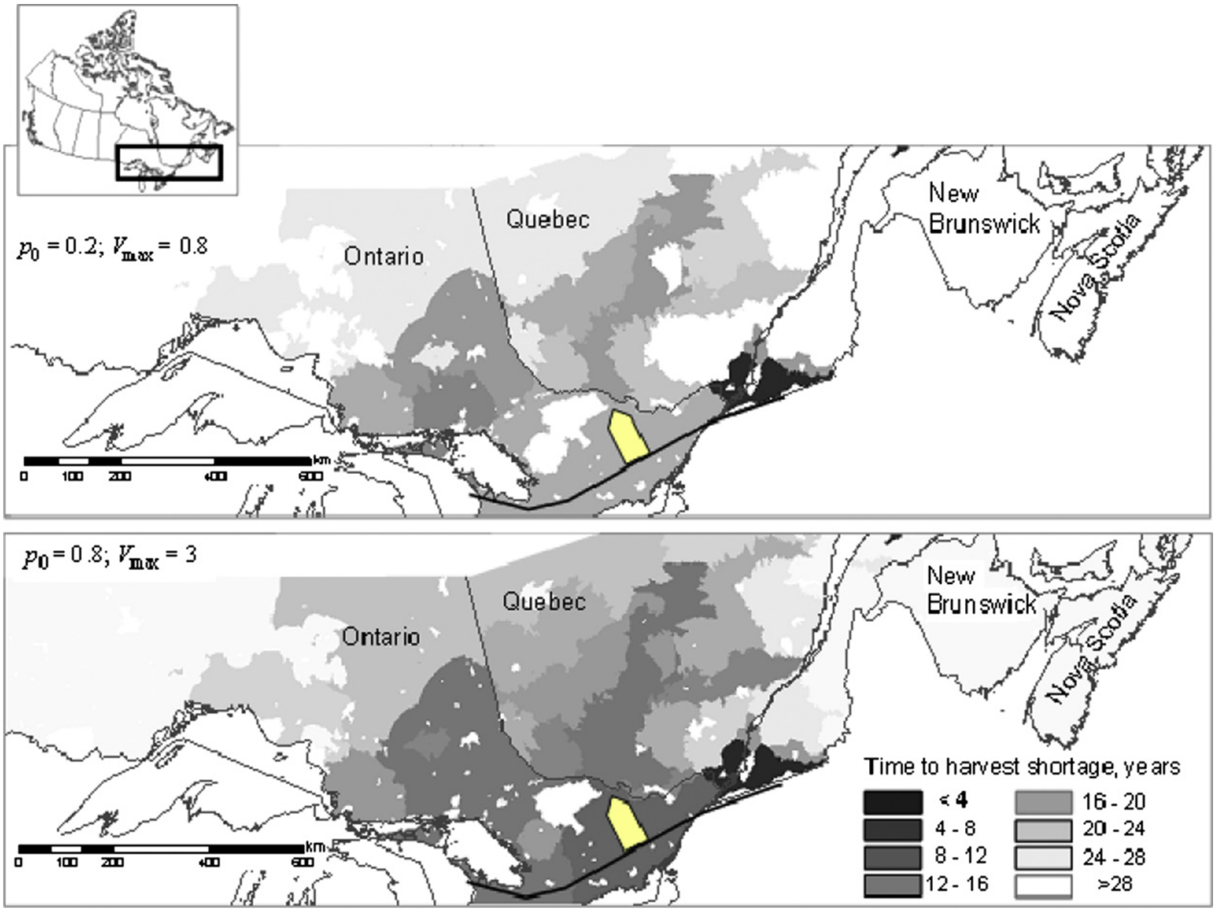

Fig. 7. Time-to-harvest shortages in eastern Canada for high ($p_0 = 0.8$; $V_{max} = 3$) and low infestation ($p_0 = 0.2$; $V_{max} = 0.8$) scenarios. The bold line shows the initial *S. noctilio* infestation and the arrow shows the direction of the invasion spread. p_0 is the probability of colonizing the nearest spatial location; V_{max} is the maximum expected annual rate of pine mortality (m^3/ha/year).

Most pest detection alerts and quarantine policies for invasive species are designed and enforced for administrative units (NYDEC, 2006; USDA, 2006; Wolff, 2005), hence area affected estimates relative to total land area may be more relevant. An example shown in Fig. 6 compares the total land area infested (which is commonly used in pest risk assessments) with the area of harvest shortages. The latter estimate is considerably lower and lags the overall infestation area. We believe this provides a more realistic expectation of the timing and extent of economic impacts from an outbreak.

3.2. Timing of large-scale wood supply failures

The timing of harvest shortages for individual FMRs is shown in Fig. 7. Based on our assumptions about *S. noctilio* behavior and expected pine mortality levels in eastern Canada, most medium-term failures were located in Ontario and Quebec within a 400-km radius of the initial detection area. A small region in southeastern Quebec (south of Montreal) had shortages predicted within 8 years. However, this region is dominated by hardwoods and has a limited pine wood supply that is just above the harvest target levels. Wood supply here is likely supplemented by imports from other regions in Canada and/or the US.

The maps did not show a semi-concentric damage pattern that might be expected based on more simpler linear rate of spread and impact model. Instead, three large and relatively homogeneous zones can be identified. The first zone, with harvest failures starting within 16 years or later, includes most of eastern Ontario and west-central Quebec. The second major zone, with harvest failures in 22–28 years, covers northeastern Ontario and northwestern Quebec. FMRs in this zone are relatively large and in some cases include the wood supply areas north of current allocations for industrial forest management (e.g., north of the 52nd parallel in Ontario). While this in principle could create additional wood supply capacity, which delays the beginning of harvest shortages, we note that, under current policy, this adjustment would not actually be possible. The third zone covers the rest of the study area (western Ontario and Maritimes) and does not show any harvest shortages within the 30-year period.

3.3. Times from the detection to a harvest failure

The model outputs offer an opportunity to estimate the time lag between the first *S. noctilio* detection in the forest region and the beginning of harvest shortages (Fig. 8). Average time between detection and onset of harvest shortage varies between 12 and 16 years, and is relatively consistent across the study area. Note however this estimate depends on the accuracy or capacity to detect new infestations. We report these periods for a range of “detection accuracies” (the thresholds denoting the minimum number of infestations, N_d, needed before *S. noctilio* is detected in the region). Poor detection leads to shorter periods between the “detection” and the beginning of harvest failures. Fig. 9 summarizes the detection-to-harvest failure times as a function of the detection

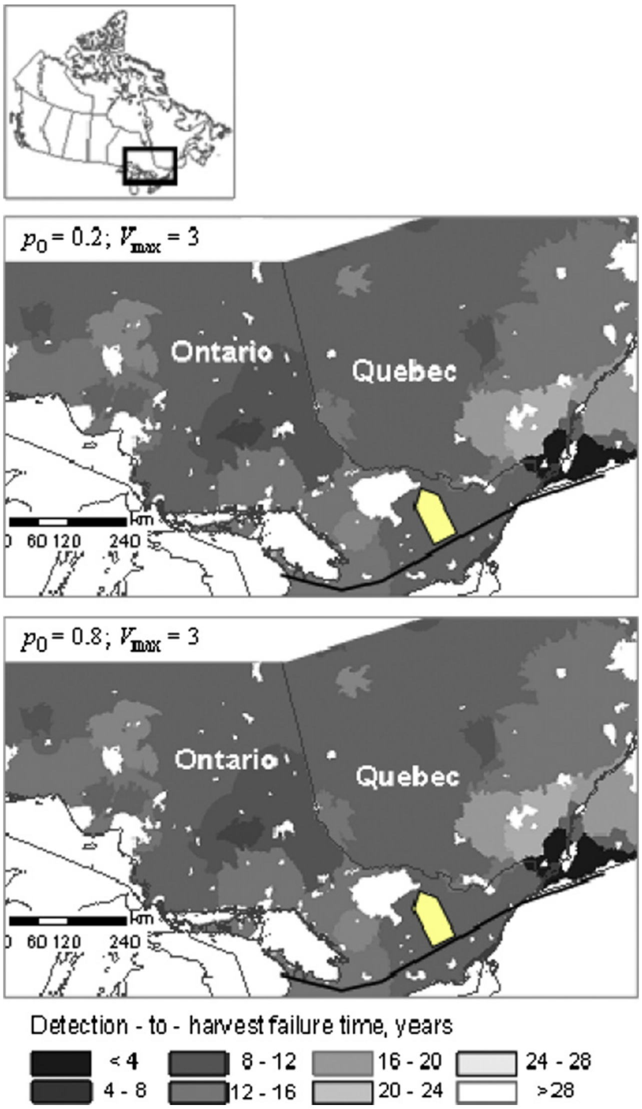

Fig. 8. Time from the first *S. noctilio* "detection" to the beginning of harvest shortages (years) in eastern Canada. The bold line shows the initial infestation and the arrow shows the direction of the invasion spread. p_0 is the probability of colonizing the nearest spatial location; V_{max} is the maximum expected annual rate of pine mortality (m^3/ha/year).

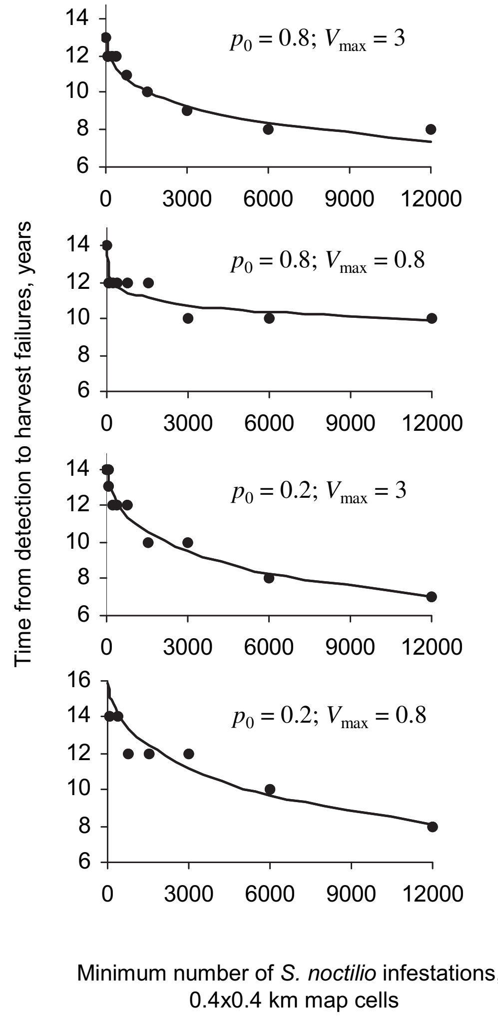

Fig. 9. Relationship between time-to-harvest failure and number of *S. noctilio* infestations required before detection occurs (years, interpolated mode values). p_0 is the probability of colonizing the nearest spatial location; V_{max} is the maximum expected annual rate of pine mortality (m^3/ha/year).

threshold, N_d^c, here fit to a decay curve, $y = 1/(a + bN_d^c)$. In most scenarios, the highest impact of the detection accuracy has been observed for the range between 0 and 500 *S. noctilio* finds per region. On average, poor detection probability shortens the time-to-harvest failures by at least 4–8 years (or approximately 32–54%). In fact, detection accuracy becomes even more important than the assumptions about the *S. noctilio* infestation and impact potential (i.e., p_0 and V_{max} values).

4. Discussion

When knowledge of a new invading organism is severely limited (which is usually the case for invasive species with no prior history in an area), it can be difficult to establish a common view on the timing and the severity of the impact. Projected estimates of infested forest area usually show a gradual increase of impact over time and rarely provide a clue when the impact of an outbreak becomes economically threatening. Our study provides an approach to estimate and make explicit when and where the invasion could cause severe consequences to regional wood supplies. The approach described here focuses on the time path of projected broad-scale physical and economic impacts via dynamic modeling rather than projections based on a static spread rate. It brings together knowledge of invasion spread and host tree mortality, explicit data on wood supply distribution and harvest activities that can be adjusted as new information about the pest becomes available. Our impact metric (a harvest failure threshold) identifies the point at which the invasion may threaten broad-scale industrial wood supply pathways (as depicted by present-day harvest levels). The time-to-harvest failure followed a piecewise pattern, making it a helpful "worst-case" policy metric. Compared to an "infested area" metric, the harvest failure area estimate may be more useful to prioritize pest management efforts as it identifies when and where the outbreak could cause irreversible economic damages. Note that we do not consider potential cost savings from harvesting alternative species or changing the wood supply region. To do this would require much more detailed knowledge on mill consumption profiles and future timber markets and is beyond our current objectives (though clearly would be of operational interest and is a longer term need).

We note that the timing and location of large-scale impacts, though dependent on general assumptions about *S. noctilio* spread, do not follow simple concentric spread patterns and semi-linear expansion of an outbreak (as would be expected from the traveling wave spread model). The timing of failures is more influenced by the size the FMR, the amount and spatial distribution of wood resources and levels of harvest within the region. For example, boreal FMRs have considerable amounts of marginal wood supply in remote locations. While more costly to reallocate harvests to more remote locations, these marginal pine resources could buy time before more massive wood shortages. For some exotic pests, this time lag may be sufficient for mitigation, management or substitution options to be developed. We recognize also that variations and alterations of regional harvest targets and the spatial arrangement of wood processing facilities could change the geographical patterns and the scale of expected impacts therefore the harvest failure estimates presented in this study should be considered as a worst-case scenario. However, it is precisely this dynamic link to the regional wood supply and current harvest activities that makes the harvest failure threshold a more appealing metric in assessing future impacts from invasive forest pests.

The timing of harvest failures also depends on long-distance spread assumptions. A recent study (Koch et al., 2009) examined the sensitivity of key parameters of a similar invasion spread model and demonstrated that the maximum annual spread rate (x_{max} that defines the long-distance spread component) was the most influential parameter on the risk of infestation. While the influence of the x_{max} on the timing of harvest failures can be significant, as noted above the occurrence of harvest failures also depends heavily on the geographic location, abundance and harvest levels of the susceptible host resource. Land managers require knowledge of the spread rate, the distribution of wood resource and allocation of harvest activities.

The results also suggest that present-day harvest activities can be used to estimate the timing between the first detection of an invading organism in an FMR and expected large-scale impacts on regional wood supply. In our example, average detection-to-harvest failure times varied between 12 and 16 years and depended on *S. noctilio* impact assumptions and detection accuracy. Poor detection rates of new infestations may shorten this period by up to 32–54% and in fact have greater impact than the assumptions about severity and spread of a new pest. This emphasizes the importance of detection and monitoring surveys for nonnative invasive species.

The probability of detection changes the perceived extent of the invasion, and may affect harvest reallocation policies to manage an outbreak. Note that in our case, a dynamic adaptation of harvest policies was not modeled explicitly (the scenarios assumed little or no flexibility of harvest policies except for adjustments of harvests within the wood supply region). Hence the issue of detection probability was not considered here. An assessment of this issue would require adding an extra decision making component to simulate detection events and dynamically adapt harvest policies in response to successful "finds" of the pest. This will be the focus of future work.

The harvest threshold approach developed here is related to the concept of resilience in ecological systems – i.e., the preservation of ecosystem functioning (and its organizational structure) in the presence of exogenous change (Holling, 1973). From a harvest threshold perspective, resilience could be considered the ability of a forest landscape to experience invasive species outbreaks without significant changes to the current nature of regional wood supplies. By incorporating economic considerations into resiliency limits, the harvest threshold approach is an important sustainability consideration for regions that depend heavily on the use of forest resources. This may be particularly important for forest landscapes that are adapted to a cyclic reoccurrence of natural disturbances (e.g., fires in boreal Canada) and thus lack the resilience to withstand new damaging agents such as invasive nonnative pests (Drever et al., 2006; Folke et al., 2004).

5. Conclusions

Invasive species are widely recognized as having far reaching consequences on forest industry and forestry-oriented communities. This is especially true for a large country like Canada with widespread and remote forests. Impacts are multi-dimensional and complex to assess. One of the most direct impacts of nonnative invasive species to Canadian forest management may be the failure to sustain long-term regional harvest objectives. While easily recognized, these impacts are hard to quantify in pest risk assessments as they arise from interactions between the spread of invasion, impacts on standing trees, biomass growth and will follow large and small-scale mitigation efforts. Our study provides a modeling approach to help identify thresholds that mark the beginning of larger-scale threats to annual harvest levels. We believe this type of information will help decision-makers better understand the extent and timing of irreversible environmental and economic changes caused by invasions and gives some indication of when and where it might occur. In the specific case study developed here, we estimate current harvest targets will be threatened when infestation levels reach approximately 12.5–14.0 M ha of pine forests in Ontario and Quebec. Regulatory agencies can use such information to assist in designing control policies and slow-the-spread programs.

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