Applying a Spruce Budworm Decision Support System to Maine: Projecting Spruce-Fir Volume Impacts under Alternative Management and Outbreak Scenarios

Chris R. Hennigar, Jeremy S. Wilson, David A. MacLean, and Robert G. Wagner

ABSTRACT

Spruce budworm (SBW) infestations and defoliation in forests of eastern North America (e.g., 1910s, 1940s, and 1970–1980s) have had significant negative impacts on growth and survival of spruce and fir. The Spruce Budworm Decision Support System (SBWDSS), originally developed by the Canadian Forest Service, can assist with SBW management planning by estimating the marginal timber supply (in cubic meters per hectare) benefits of protecting stands against budworm defoliation. We applied the SBWDSS to Maine and for two private forests (≈10,000-ha townships) to assess potential spruce-fir losses. Application of the approach across diverse forest types and data sets revealed dramatic differences in potential volume impacts between the two townships. The statewide analysis suggested that over 4 million ha of Maine's forest are vulnerable to the budworm. Projections of moderate and severe intensity outbreaks reduced statewide spruce-fir inventories by 20–30% over the next 10 years.

Keywords: *Choristoneura fumiferana*, Spruce Budworm Decision Support System, timber supply, salvage harvesting, Woodstock, scenario analysis, Maine

Northeastern forests of the United States and Canada have long been subject to cyclical spruce budworm (SBW; *Choristoneura fumiferana* Clem.) outbreaks (Royama et al. 2005), and another outbreak will probably occur in Maine within the next 10 years. SBW host species include balsam fir (*Abies balsamea* [L.] Mill.) and white (*Picea glauca* [Moench] Voss), red (*Picea rubens* Sarg.), and black spruce (*Picea mariana* [Mill.] BSP).

The Spruce Budworm Decision Support System (SBWDSS), originally developed conceptually by Erdle (1989) and refined into a software application by the Canadian Forest Service (MacLean et al. 2001), can be used to assist with SBW management planning by quantifying the marginal timber supply benefits from protecting stands against budworm defoliation. The SBWDSS allows users to assess the effects of different SBW outbreak scenarios and foliage protection (insecticide use) strategies on forest development and values, and to quantify the relative timber volume benefit of alternative spray blocks (MacLean et al. 2000a, 2002). The SBWDSS has been used by public (e.g., Canadian Forest Service, New Brunswick Department of Natural Resources) and private agencies (e.g., BioForest Technologies, Inc., Forest Protection Limited) in New Brunswick, Ontario, and Saskatchewan to quantify SBW defolia-

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tion effects and minimize spruce-fir harvest losses.

Recently, the SBWDSS has been improved to include better (1) stand-species impact resolution (separation of host species defoliation and volume impact projections; Hennigar et al. 2008) and (2) integration of stand impact projections with industrial-scale timber supply models such as Woodstock (Remsoft, Inc., 2007), thus allowing optimized replanning of the harvest schedule and salvage of budworm-killed timber volume (Hennigar et al. 2007). This integrated model framework allows for linear optimization of forest pest management objectives (e.g., timber supply, habitat, foliage protection, and net revenue).

The objectives of this study were to (1) apply the SBWDSS framework spatially to two ≈10,000-ha townships in Northeastern and Southeastern Maine to test the feasibility of using the SBWDSS on forested landscapes with different levels of inventory and management planning data typically found in the Northeastern United States, and (2) use the USDA Forest Inventory and Analysis (FIA) data to assess potential spruce-fir losses from a SBW outbreak in Maine.

Methods

Data

Two Maine townships (Figure 1) were selected to represent a range of forest information and stand types typically found in the Northeastern United States. Those selected included a 25,946-ac (10,500 ha) Northeastern Township owned by J.D. Irving Limited, and a 23,969-ac (9,700 ha) Southeastern Township managed by American Forest Management. Inventory and stand maps were provided by the companies. The Northeast and Southeast forests contained 21,622 and 20,707 ac (8,750 and 8,380 ha) of productive forest, respectively, with 78 and 85% of stand type area considered susceptible (≥10% of spruce-fir current inventory volume) to SBW.

To conduct a statewide spruce-fir impact assessment, over 3,000 USDA FIA plots from Maine were downloaded from the FIA DataMart (download date Nov. 12, 2008; Miles et al. 2001) as database files. Plot inventories from 2002 to 2006 were selected and formatted for use with the database extensions of the Forest Vegetation Simulator Northeast Variant (FVS NE; Dixon 2002). All plots were projected to 2008 and then in 5-year increments for an additional 25 years using FVS NE. Projected FIA plots were then stratified into SBW stand impact types (see Table 3). The area and spruce-fir volume represented by each of these plots was determined from expansion factors in the FIA database.

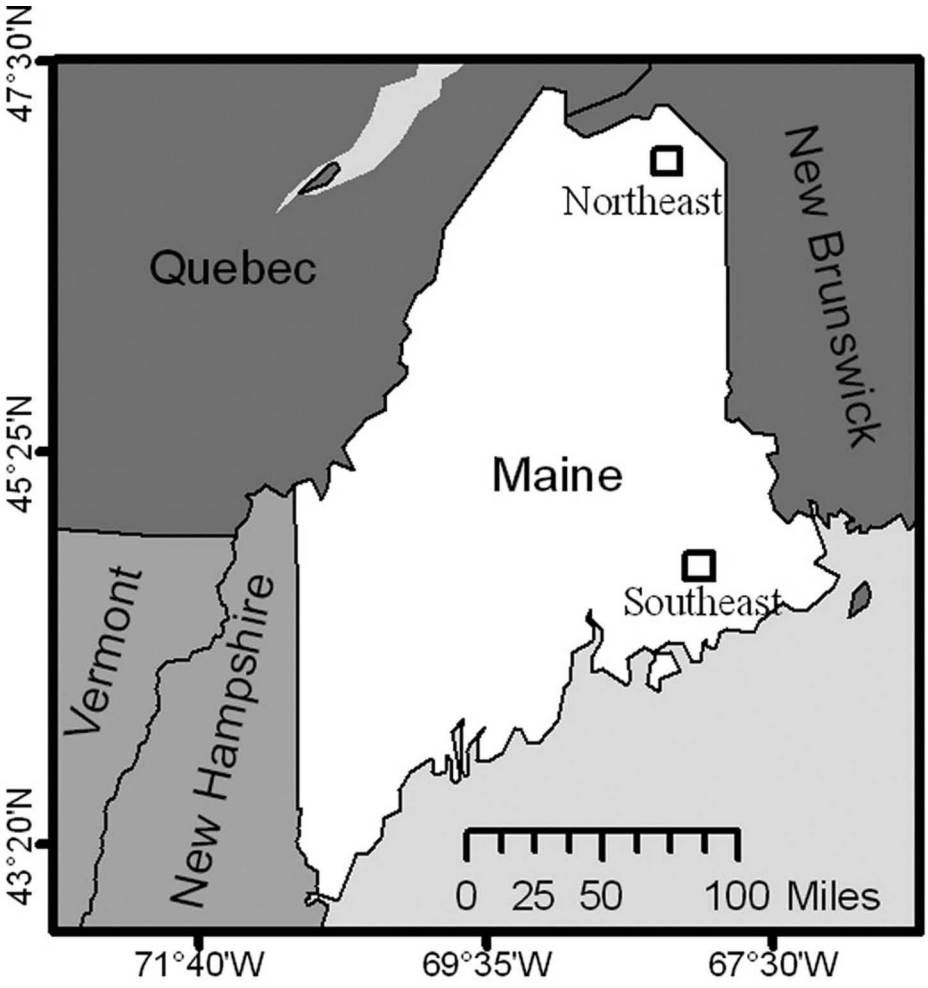

Figure 1. Location of the Northeast and Southeast Townships in Maine.

Defining SBW Outbreak Scenarios

"Moderate" and "severe" SBW outbreak scenarios were adopted from previous New Brunswick SBWDSS impact studies (MacLean et al. 2001, 2002). Each outbreak scenario is a temporal sequence of annual defoliation levels during a hypothetical future outbreak, without aerial spray protection. The moderate outbreak scenario was originally derived by Erdle and MacLean (1999) from population dynamics presented by Royama (1984) and discussions with New Brunswick Department of Natural Resources staff. The severe outbreak scenario emulates a similar scenario as the moderate outbreak, but with prolonged severe defoliation (2 more years at 100%), as was observed in Cape Breton, Nova Scotia, during the 1970–1980s budworm outbreak (MacLean and Ostaff 1989).

Given that most trees sampled during the last outbreak (1970–1980s) for monitoring SBW populations were balsam fir, outbreak scenarios represent balsam fir defoliation trends. Hennigar et al. (2008) showed consistent, significant differences in defoliation levels of white, red, and black spruce relative to that of balsam fir. To reflect these host susceptibility differences in some scenarios, white, red, and black spruce defoliation was approximated as 72, 41, and 28% of balsam fir defoliation, respectively (within ±5% of curvilinear linear models reported by Hennigar et al. 2008). Relative differences among species may become diluted at very high defoliation levels (more than 90%; e.g., Blais 1957, Nealis and Régnière 2004). Following methods from Hennigar (2009), to reflect this difference, spruce defoliation was assumed to be the same as for balsam fir when fir defoliation was more than 90% for all scenarios. Maine

forest composition is, in general, less susceptible to SBW than in New Brunswick, with stands composed of more nonhost softwood and hardwood species, and a higher percentage of less preferred red and black spruce of total host species. During a large SBW outbreak, reduced abundance of preferred host (balsam fir and white spruce) in Maine may cause increased feeding on less preferred host (red–black spruce) and reduce differences between spruce and balsam fir projected defoliation levels to less than those found in New Brunswick by Hennigar et al. (2008). To capture the range of potential volume impacts for alternative assumptions of spruce susceptibility to defoliation, all scenario combinations were modeled with spruce defoliation scaled according to Hennigar et al. (2008) and again with balsam fir defoliation levels applied to all host species as modeled in MacLean et al. (2001).

Outbreak and Protection Scenarios

Including the base (no defoliation) scenario, 11 outbreak and protection scenarios were simulated. These included moderate and severe outbreaks (beginning in 2010), combined with foliage protection scenarios using applications of biological insecticide (*Bacillus thuringiensis*) in all years when balsam fir defoliation was more than 40% across 10, 20, 40, or 70% of susceptible area. Protection was assumed to reduce current-year defoliation to 40% in all scenarios (based on the New Brunswick provincial protection target; e.g., Carter and Lavigne 1994). Additional scenarios were performed to quantify effects on long-term harvest level of applying salvage harvest and replanning the treatment schedule for the Northeast Township.

Assignment of stand areas for protection was prioritized by selecting the most vulnerable stands (measured during the highest projected volume lost period, 2025–2029) to maximize the volume benefits of additional area protected. Alternatively, if time of harvest is known, or if a timber supply model is available (as in the Northeast Township), protection can be assigned to areas with explicit consideration of the harvest schedule to further increase harvest benefits of area protected and avoid protecting areas that will be harvested in the first 10 years of the outbreak (Erdle 1989).

Prediction of SBW Volume Impacts

An SBW stand impact matrix (Erdle 1989, MacLean et al. 2001, Hennigar et al. 2007; Figure 2) was developed, which specified marginal changes to stand volume for each defoliation scenario by stand type and maturity. Combinations of outbreak defoliation patterns and foliage protection resulted in four current defoliation scenarios, which were condensed into three similar (within 10%) cumulative defoliation scenarios (moderate, severe, and protected). Cumulative defoliation is used by the New Brunswick growth-and-yield model, STAMAN (Erdle and MacLean 1999), to predict SBW impacts on tree growth loss and mortality (Figure 2). The stand impact matrix used here was calculated using data from over 11,000 forest development survey plots measured in stands throughout New Brunswick, ranging from tolerant hardwood-spruce to pure balsam fir and with ages between 10 and 150 years old. Stand tables compiled from survey plots were projected using STAMAN, with and without defoliation, to quantify relative host species volume impacts and salvageable volume over time (Figure 2).

Separation of host species explained some impact differences between stand types, allowing the 53 stand impact types defined in past SBWDSS analyses (Table 1 in MacLean et al. 2000b) to be collapsed into 20 (Table 1). Standard error of relative host volume impacts (percent of base yield volume) within stand impact types varied by less than ±1% 15 years following initiation of a severe budworm outbreak. Because relative impacts vary little across stands within types (as shown in Figure 10 of Erdle and MacLean 1999), it is assumed here that relative impacts can be applied to similar stand type volume projections in Maine. This assumption simplifies SBWDSS implementation by avoiding growth and survival calibration and stand table initialization of STAMAN for Maine stands and allows existing yield projections available in each township to be used.

Application of SBWDSS to Maine Data

Three forest information sources are required for calculation of future spruce-fir inventory impact using the SBWDSS framework: (1) area of stand types (geographic information system [GIS]), (2) classification of current land base stand types by budworm stand impact type (volume composition and age dependent; Table 1), and (3) host species volume projections for each stand type. This information provides the necessary information to link to relative volume impacts in the SIMPACT by defoliation scenario (Figure 3). Relative time-dependent volume impacts are multiplied against base yield volumes for each area record to calculate absolute volume impact across space and time. Projections of impact allow managers to concentrate harvest and foliage protection efforts in areas with the highest potential volume loss first.

Both townships and the statewide inventory had projections of stand growth over time and an estimate of stand area. The Northeast Township and statewide data sets had wood volume yields for each host species, whereas the Southeast Township did not (spruce-fir grouped). To separate the host yields from grouped spruce-fir projections for the Southeast Township, percentage host composition defined in the current GIS inventory for each stand type was multiplied by spruce-fir yields. Volume composition of species and maturity class for each stand type were used to classify stands by stand impact type (Table 1). Stands were defined as mature (more than 40 years old) or immature on the Northeast Township by treatment condition: planted, precommercially thinned (PCT), and commercially thinned conditions as immature (99% currently less than 40 years old); and unmanaged or partial cut as mature. Age from the statewide inventory was used to determine whether stands were immature or mature. No age or development stage attributes were available for Southeast Township stands; yield projections of the current inventory are time based, therefore, age was not required. Height class was used as a surrogate for stand age for the Southeast Township, where height classes 1–2 (0–10 m) were assigned as immature and 3–4 (more than 10 m) as mature.

Standing inventory was grown forward to 2010 and 2012, respectively, for the Southeast and Northeast Townships before outbreak initiation in 2010. The 2012 Northeast inventory is presented henceforth as 2010 inventory so similar outbreak defoliation sequences and start periods could be applied to each township for comparison purposes and to simplify the presentation and explanation of results. Statewide FIA plots were "grown" forward to a common start year of 2008 and an outbreak inception in 2010.

In general, the Northeast susceptible area contained higher concentrations of balsam fir– and white spruce–dominated stands than the Southeast forest. Predominant susceptible stand type area in the Northeast included balsam fir or white

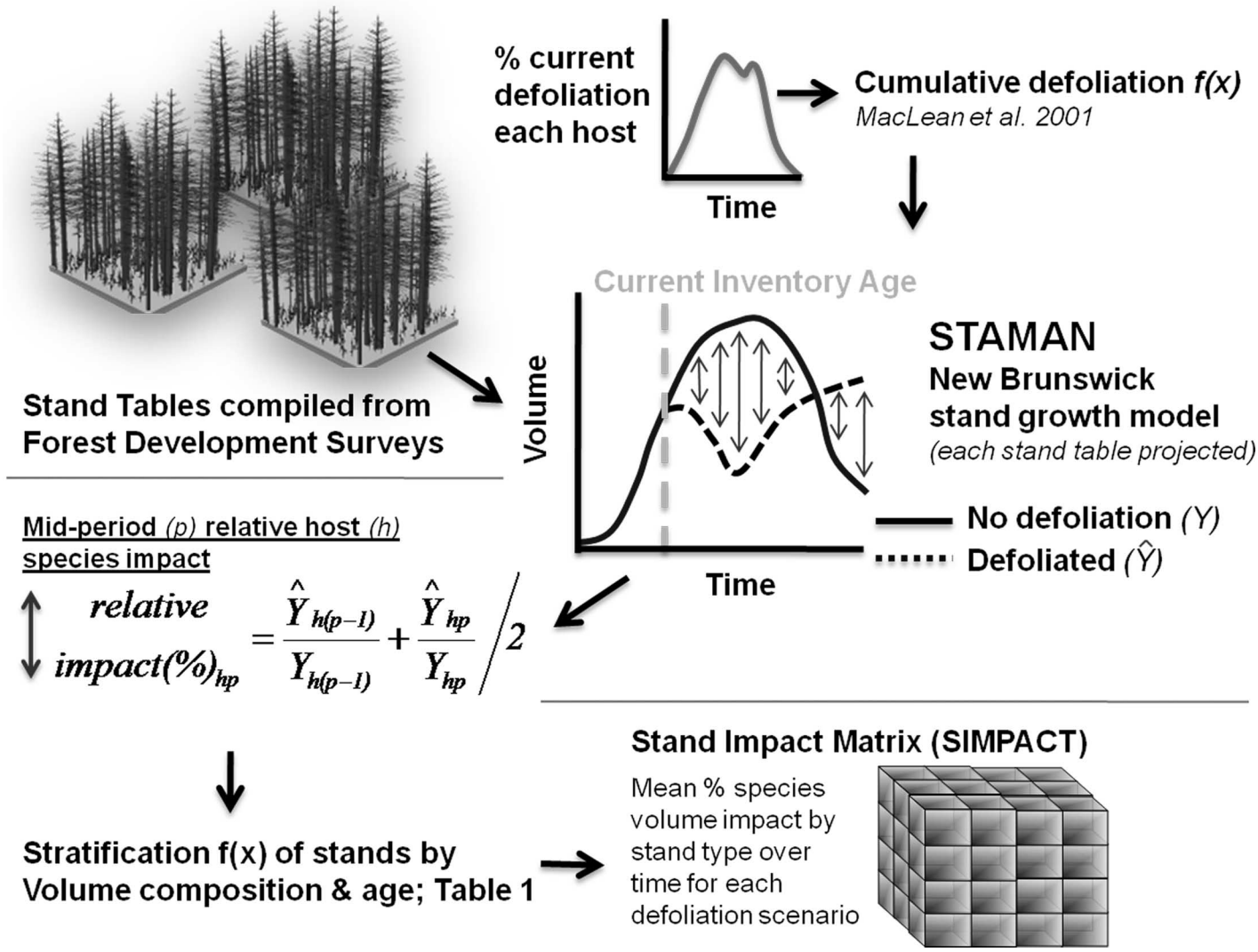

Figure 2. Steps to construct the SBWDSS stand impact matrix. Percent species impact represents volume remaining by species for defoliated relative to undefoliated yield over time. Calculation of relative periodic salvageable volume is similar, except only volume of periodic mortality caused by SBW is compared against no defoliation yield projections.

Table 1. Spruce budworm stand impact stratification criteria (percent volume loss over time) by species composition.

Species composition (%)		
Spruce–fir	Fir–white spruce	Impact type
75–100	75–100	FW
	50–74	FWRB
10–74	<50	RBFW
	50–100	FWMX
	<50	RBMX
<10		NH

Impact types were also separated by maturity (see Table 2) and management history: (i) planted or precommercially thinned or both, or (ii) not; not shown.
FW, balsam fir or white spruce, RB, red and black spruce; MX, mixed nonhost; NH, nonhost.

spruce or both (8%), spruce plantations, and spruce-fir PCT and commercially thinned (25%) and fir-spruce–dominated mixed wood (39%). In contrast, the Southeast susceptible area contained mostly mixed wood types, with 87% of mixed wood stands comprised of less than 50% host species dominated by red or black spruce or both, and the remaining 13% comprised of 50–80% host species dominated by balsam fir and or white spruce or both (Table 2; Figure 4).

A series of select and action queries were developed in a Microsoft Access database to link future stand conditions (time or age or both, host species yield) with the stand impact matrix to quantify volume losses over time for outbreak and protection scenarios. The maximum volume loss for each stand 15 years post–severe outbreak initiation (2025–2029; Figure 5) was used to rank stands for simulated foliage protection priority, where area with highest volume loss was selected first for protection across 10, 20, 40, or 70% of susceptible area.

Timber Supply Projection—Northeast Township

More informed pest management decisions can be made if the forest harvest schedule is known or can be projected. Quantifying impact at the time of harvest allows for more effective spatial prioritization of foliage protection treatments; e.g., mature fir-spruce (highly vulnerable) stands destined for harvest during the first 1–10 years of the outbreak will not require protection, whereas young spruce plantations harvested in 15–25 years may require foliage protection to keep trees alive and reduce growth loss to meet planned harvest levels. Integration of the stand impact matrix directly into

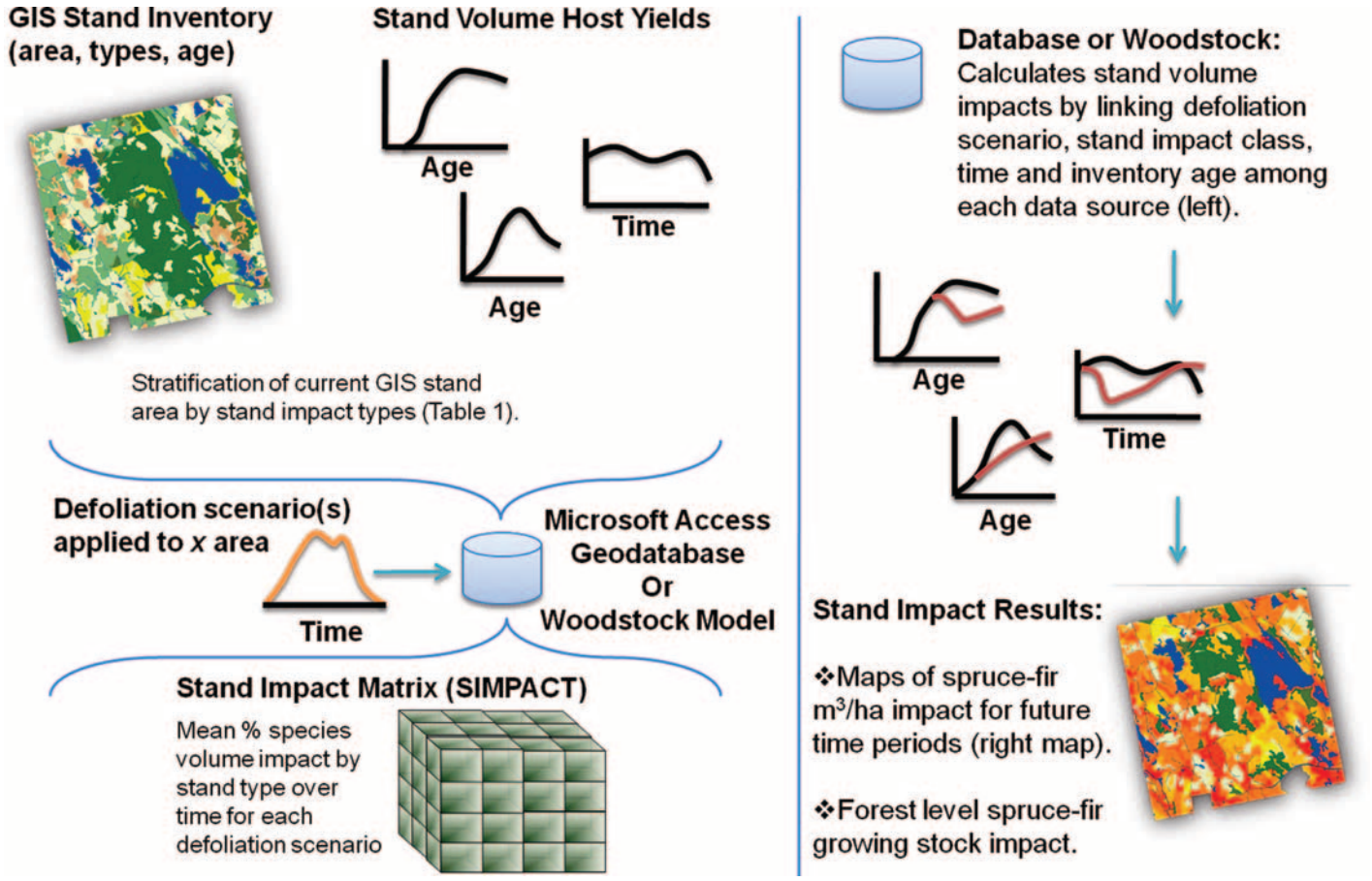

Figure 3. Schematic representation of information sources used and application in the SBWDSS to calculate spruce-fir stand volume impacts and operable salvage volume over time.

Table 2. Percentage of Township area susceptible to SBW categorized by spruce–fir volume loss by 2025 and stand impact type for a severe outbreak.

Volume loss class (m^3/ha)	Percentage of area by township, spruce-fir volume loss class, and stand impact type[a,b]									
						Managed (PCT or planted)				
	FW-M	FWMX-I	FWMX-M	RBMX-I	RBMX-M	FW-I	FWMX-I	RBFW-I	RBMX-I	Total
Northeast Township										
20–39	—	—	18	—	26	—	—	8	2	55
40–59	—	—	17	—	1	7	8	—	—	33
60–79	8	—	4	—	—	—	—	—	—	12
Total	8	—	39	—	27	7	8	8	2	100
Southeast Township										
20–39	—	0	—	27	56	—	—	—	—	84
40–59	—	13	—	3	—	—	—	—	—	16
Total	—	13	—	30	57	—	—	—	—	100

Total area susceptible was 16, 976 and 17,569 ac (6,870 and 7,110 ha) for the Northeast and Southeast Township, respectively.
[a] Types having less than 1% area not shown.
[b] Stratified stand impact types shown are also broken down by stand development stage for immature (I; ≤40 yr old) and mature (M; more than 40 yr old), with the maturity designation appended to the end of the impact-type name.
FW, balsam fir or white spruce, RB, red and black spruce; MX, mixed nonhost; NH, nonhost.

a timber supply modeling environment allows harvest schedules to be replanned to minimize harvest volume losses (Hennigar et al. 2007) for different defoliation scenarios. This integrated framework can simultaneously schedule salvage and foliage protection treatments, e.g., to maximize volume return for a given protection budget constraint.

The J.D. Irving Limited, forest estate model built in Woodstock (Remsoft, Inc., 2007) by the company in 2007 to forecast timber supply for all Maine holdings was simplified to include only stand area, yields, treatments, and treatment operability and posttreatment stand responses common to the Northeast Township area used here. The J.D. Irving Limited planning objective (formulated as a linear programming objective function in Woodstock), to maximize spruce-fir harvest, and nondeclining harvest

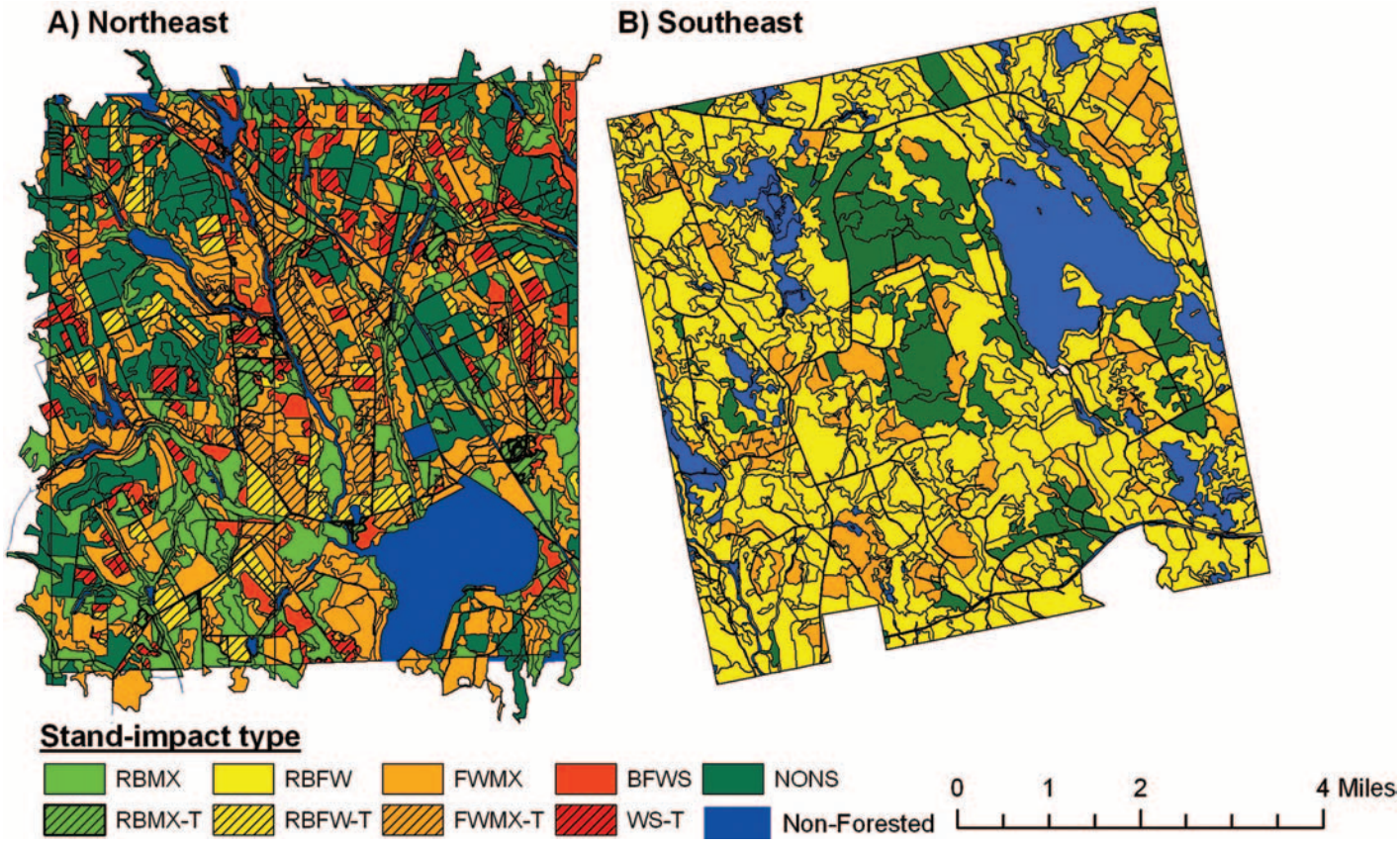

Figure 4. Forest susceptibility by budworm stand impact type (Table 1) for (A) Northeast and (B) Southeast Townships. Stand types with less than 1% area not shown. Types designated by a "T" suffix are planted or thinned.

and inventory constraints (after 2050) were retained. Constraints on area of silviculture over time were scaled in equal proportion to the area reduced from the original (all holdings) to the simplified township model. This model formulation was used as the base no SBW defoliation scenario. An additional GIS theme was added to identify SBW impact zones to allow for development of an outbreak protection scenario. The simplified model formulation included 231 stand types with merchantable yields (in cubic meters per hectare) by species and treatment (partial cut, shelterwood, select cut, commercial thin, clearcut, planting, and PCT).

Areas harvested were assumed to remove salvageable volume in direct proportion to volume removed during that treatment (e.g., clearcut = 100% and partial cut ≈ 30% removal of budworm-caused mortality). In practice, a partial harvest operation would target budworm-caused mortality; thus, this may underestimate salvaged mortality.

Mortality generally begins 5–7 years after the onset of severe defoliation and is near complete after 10–12 years (MacLean 1980, Blais 1983, MacLean and Ostaff 1989). Moderate (≥50%) to high (≥70%) defoliation for outbreak scenarios was projected to begin in 2015 and subside in 2024; hence, we would expect the majority of dead or dying volume to be available in the 2020–2024 planning period. Volume dying by the end of 2015–2019 was available to be salvaged as mostly live volume during that period and added to the cumulative dead or dying volume available for salvage for 2020–2024. Fungus growth and decay in dead trees causes rapid reduction in the quality of salvageable volume, with balsam fir generally salvageable for 1–3 years after death (Basham and Belyea 1960, Blum and MacLean 1985, Basham 1986) and spruce up to 3–5 years in the case of pulpwood (Sewell and Maranda 1979). Therefore, volume dying in the 2020–2024 period was not considered as operable inventory from 2025 to 2029.

The J.D. Irving Limited objective function was modified to minimize the maximum defoliation-caused harvest reduction through iterative reoptimization methods described by Hennigar et al. (2007). We omitted nondeclining spruce-fir harvest constraints until 2024 to avoid infeasibilities due to unavoidable harvest reductions from SBW-caused growing stock mortality.

Results and Discussion

Application of the SBWDSS Framework to Each Township

Using species-specific defoliation predictions, potential spruce-fir inventory reduction, in 2020–2024, ranged from 15 to 30% for moderate and severe outbreak scenarios with no interventions in the Southeast and from 34 to 47% in the Northeast Township (Figure 6). When using balsam fir defoliation predictions, the predicted losses in spruce-fir inventories between the two townships were very similar. This disparity highlights how balsam fir is much more prevalent in the Northeast Township (Table 2). Because the Southeast Township has a high proportion of less susceptible host species compared with the Northeast, stand impact projections were more sensitive to uncertainty of defoliation (susceptibility) dissimilarity between hosts (Figure 6).

Given that projected defoliation may be less severe for the Southeast because of the higher host composition of red and black

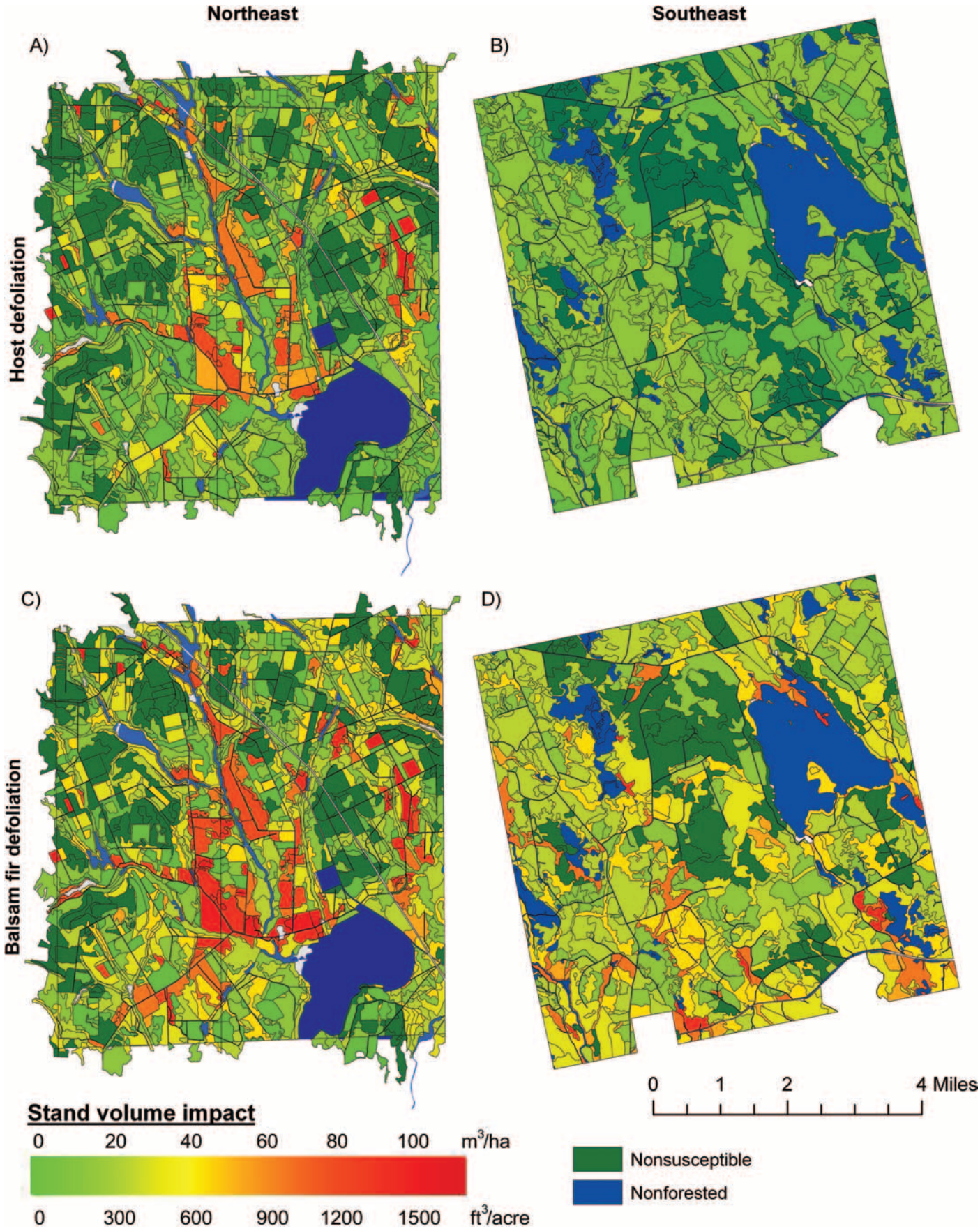

Figure 5. Projected 2025–2029 merchantable inventory reduction for the (A and C) Northeast and (B and D) Southeast Townships caused by a severe SBW outbreak initiating in 2010 using (1) reduced defoliation on spruce relative to balsam fir (panels A and B) and (2) spruce species defoliation equal to balsam fir levels (panels C and D). Future forest condition does not consider harvesting.

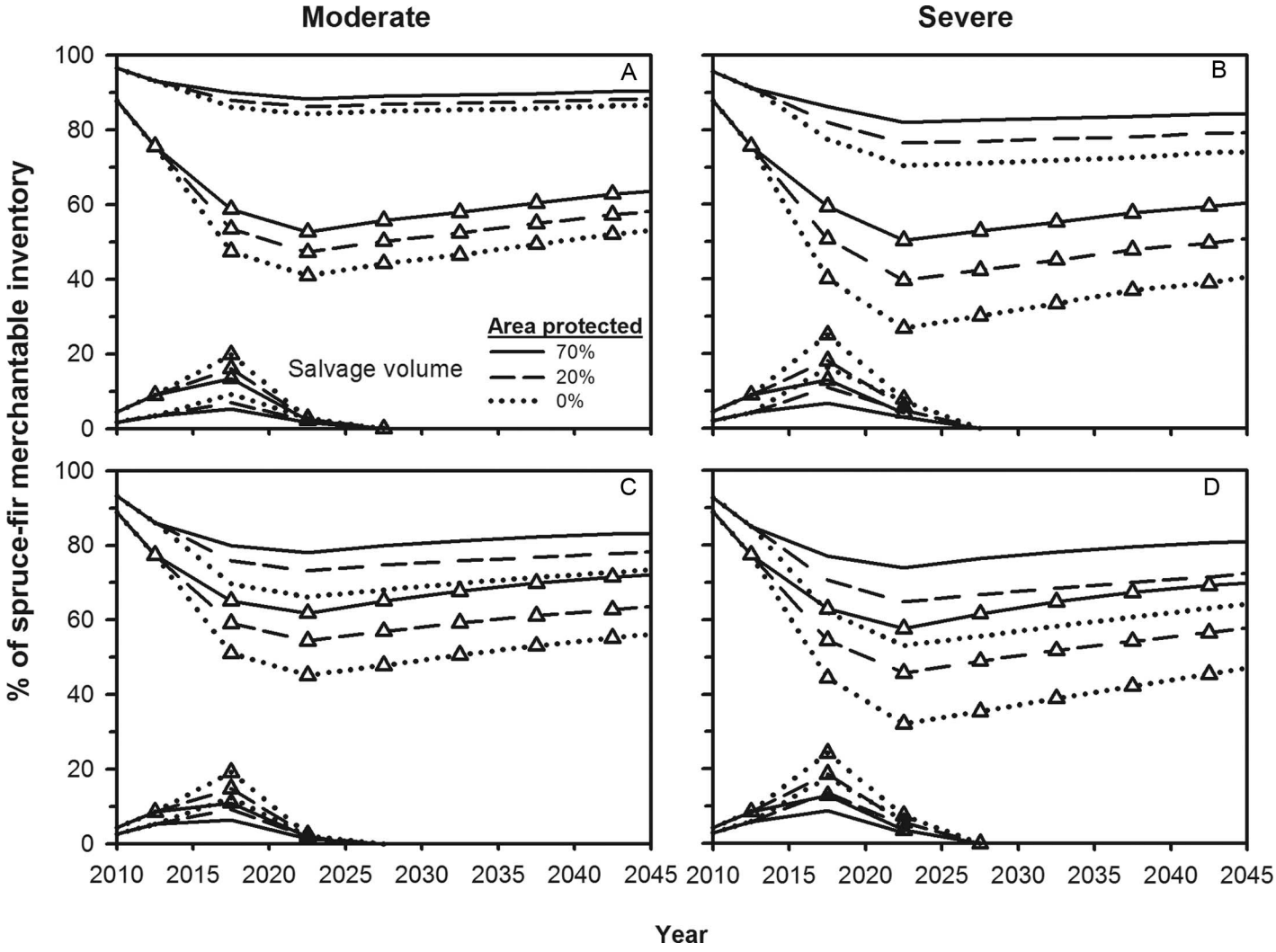

Figure 6. Percent of base (no spruce budworm defoliation) spruce-fir inventory projected with no harvest on the (A and B) Southeast and (C and D) Northeast Township for a moderate and severe SBW outbreak beginning in 2010 with (i) no foliage protection, (ii) foliage protection applied to 20%, and (iii) 70% of susceptible area. Triangle symbols denote scenarios with balsam fir defoliation levels applied to all species, and no symbols denote scenarios of reduced defoliation on spruce species relative to fir.

spruce than in the Northeast Township (Figure 4), management strategies to reduce impact could put more emphasis on targeted removal of dying trees within stands, rather than complete stand removal, and use applications of insecticide on only isolated high-impact stands, rather than delineating large 250- to 1,200-ac (100–500 ha) spray blocks comprised of many stands. In the Southeast, landowners may opt to exclude pest management if hardwood, pine, or nontimber management objectives are considered more important than spruce-fir harvest and if stands are expected to be resilient (nonhost stand response and gap disturbance regeneration).

Available salvage volumes peak across both townships and all scenarios during the first 10 years and quickly decline to zero by the end of the second 10 years. This pattern reflects the onset of maximum mortality and then subsequent loss of salvageable material through decay. The amount of salvageable volume is considerable; however, its availability is concentrated in a short window compared with the long-term impacts on spruce-fir volumes seen in both townships.

Foresters may be faced with a difficult choice—salvage or protect? Policies to govern salvage operations (minimum operable volume, riparian buffer widths, and onsite deadwood retention) and potential markets (wood quality limits and percent of poor quality wood that mills can reasonably accept) should be identified well in advance of an outbreak. Maps that spatially quantify salvageable volume, road access, and harvest volume benefits of foliage protection can be developed now and updated during an outbreak. Areas with poor road access, low salvageable volume, or young stands that are planned to sustain future harvest levels are prime candidates for protection rather than salvage.

Timber Supply Projection—Northeast Township

Harvest reductions associated with simulated SBW infestation on the Northeast study area are presented as percent of planned harvest levels without defoliation in Figure 7. The planned harvest scenario sought to maintain current harvest levels throughout the projection. Predicted spruce-fir harvest reductions are more dramatic than the inventory declines shown in Figure 6, A and C. SBW impacts are greater in more mature stands. These mature stands are supplying harvest volume for the first

half of the scenario; therefore, the impact on harvest volumes is larger than on standing volumes. Large declines in harvest levels continue throughout the 40-year scenario depicting the long-term nature of impacts associated with budworm damage.

The results suggested that harvest reductions associated with an SBW outbreak could be dramatically reduced through salvage and replanning of the harvest schedule. Where species-specific defoliation rates were evaluated (Figure 7, B and D), salvage and replanning reduced maximum harvest volume reductions from 35 to 10% and from 50 to 15% for moderate and severe outbreaks, respectively. Where balsam fir defoliation rates were used for all species (Figure 7, A and C), the improvements made through salvage and replanning were not as dramatic. This result suggested that Woodstock took advantage of variations in species-specific stand susceptibility to mitigate harvest reductions through replanning. Furthermore, reductions in harvest losses associated with foliage protection, in addition to salvage and replanning, were more limited than those from just salvage and replanning in this particular landscape and scenario.

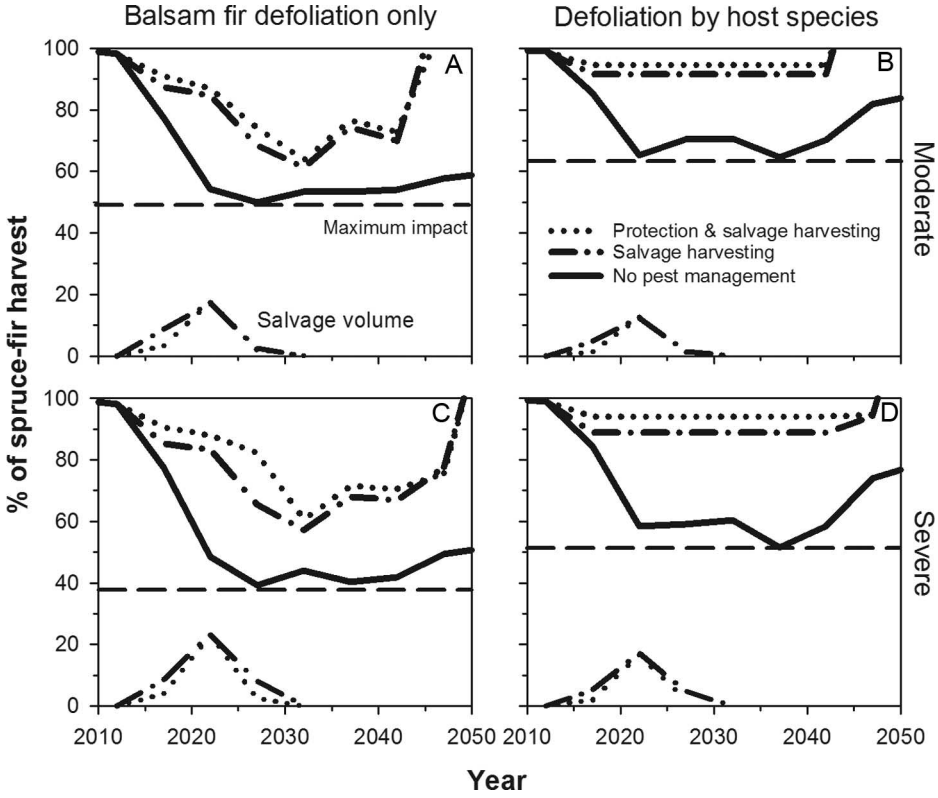

Figure 7. The three top lines in each graph show percent harvest reductions from current harvest levels (no budworm defoliation) caused by budworm defoliation. Spruce-fir harvest is shown for the Northeast Township for (i) budworm outbreak with no pest management; (ii) outbreak with salvage and replanning; and (iii) outbreak with salvage, replanning, and 20% susceptible area protection. Each is shown for moderate and severe outbreak scenarios and for (A and C) fir defoliation level applied to all species and (B and D) reduced defoliation on spruce species relative to fir.

Statewide Analysis

The statewide analysis of FIA data suggests that over 10 million ac (4 million ha) in Maine have ≥10% of their volume in susceptible species (Table 3). In simulations of a moderate intensity outbreak, using species-specific defoliation rates and with no insecticide protection, starting in 2010, spruce-fir inventories would be reduced by more than 23% by 2020 (Figure 8). This loss climbed to more than 32% in a simulated severe outbreak. When balsam fir defoliation rates were used, spruce-fir inventory reductions increased to 52 and 60% for moderate and severe outbreaks, respectively. The statewide impact is intermediate between impacts predicted in the Northeast and Southeast areas, suggesting the two study townships captured a wide range of forest types vulnerable to SBW. A large increase in reductions associated with using balsam fir rather than host-specific defoliation predictions in the statewide analysis mirrored results for the Southeast Township and emphasizes the importance of red and black spruce in Maine. As a result, careful monitoring of species-specific defoliation levels during SBW outbreaks in Maine will be required to ensure host species impact relationships developed in New Brunswick are applicable.

Table 3. 2008 spruce–fir (SF) volume and area in Maine by spruce budworm (SBW) stand impact type (Table 1).

SBW impact type	Area		SF volume (million ft^3)	SF volume (million m^3)
	Acres	Hectares		
FW-I	329,088	133,175	88	2.5
FW-M	112,908	45,692	106	3.0
FWMX-I	207,015	83,774	74	2.1
FWMX-M	268,446	108,634	211	6.0
FWRB-I	137,260	55,546	64	1.8
FWRB-M	89,508	36,222	110	3.1
RBFW-I	263,108	106,474	68	1.9
RBFW-M	776,555	314,255	976	27.6
RBMX-I	1,648,945	667,292	328	9.3
RBMX-M	6,423,593	2,599,487	3,459	98.0
Total	10,256,426	4,150,551	5,485	155.3

Estimates based on FIA (2002–2006) plots in Maine and FVS NE projections.
FW, balsam fir or white spruce; RB, red and black spruce; MX, mixed nonhost; NH, nonhost; I, immature; M, mature.

Limitations

Harvest and inventory impacts from SBW modeled here are believed to be conservative for a number of reasons as outlined by Hennigar (2009):

1. Forecasts use optimum planning using a deterministic SBW outbreak. In reality, spatiotemporal outbreak projections will change over time as more population data and aerial sketch mapping information becomes available during the outbreak.
2. All township area was assumed accessible

for salvage and protection operations (generally probable for most areas in Maine) and areas assigned for protection were assumed 100% effective in reducing defoliation to 40% (less probable; Fleming and van Frankenhuyzen 1992, Régnière and Cooke 1998).

3. Stand operability (earliest treatment age or time; generally defined by minimum mean stand volume per tree or volume per hectare) was not adjusted to account for SBW effects, nor were product log:pulp ratios, despite reduced growth and quality deterioration caused by defoliation.
4. The STAMAN defoliation-damage function does not directly account for reduced tree height growth and top-kill typically observed in attacked stands (Baskerville and MacLean 1979, Krause et al. 2009).
5. Stand impacts of other secondary disturbances, such as wind and disease, are exacerbated by SBW defoliation (e.g., reducing tree vigor and increasing stand canopy disruption). These effects are not calibrated in STAMAN, thereby underestimating stand breakup and long-term stand decline after an outbreak (Taylor and MacLean 2009).
6. Mean defoliation patterns were used, whereas in reality, spatiotemporal defoliation patterns vary widely between and within stands, and because survival declines nonlinearly with increased defoliation, survival may be overestimated.

Despite these known model shortfalls to predict absolute future harvest or stand impact, proportional differences in harvest impact compared between management scenarios are less subjective when management choices are tested individually (salvage or no salvage; Hennigar et al. 2007, Hennigar 2009).

Conclusion

The Northeast and Southeast Townships provide useful examples of how the SBWDSS can be applied throughout Maine, despite seemingly large differences among landowner forest inventory and GIS data resolutions and formats. This study also shows the range of SBW impacts that may be expected across Maine, from high impact in areas such as the Northeastern Township to moderate impacts in areas such as the Southeastern Township, resulting from decreased host content in stands (Figures 4 and 6).

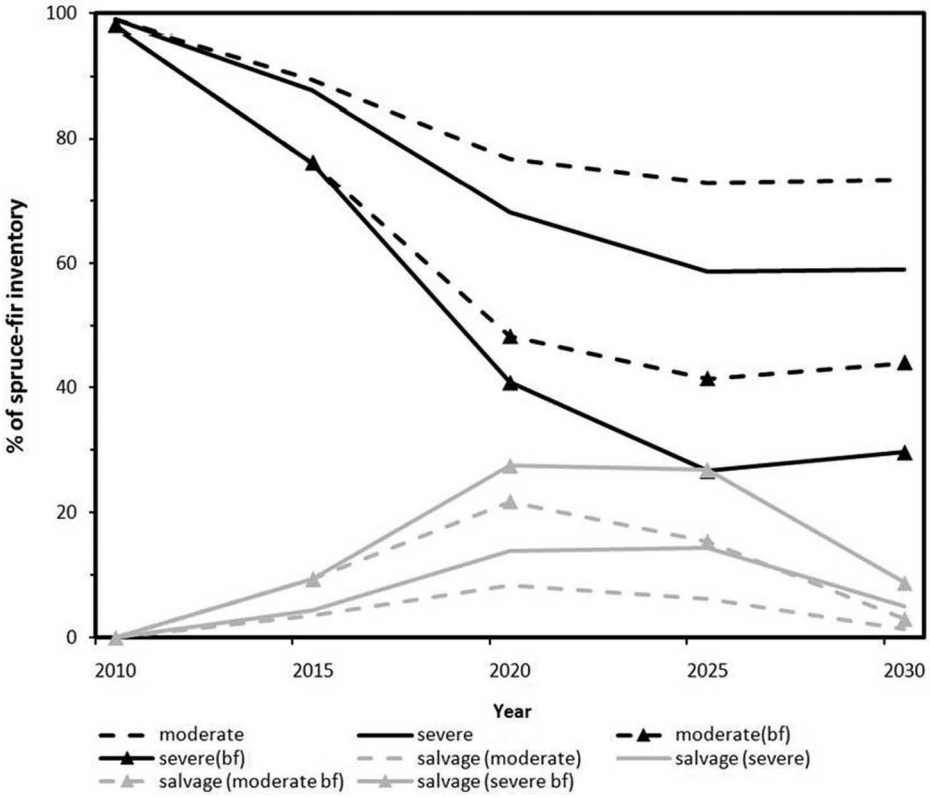

Figure 8. Percent of base (no SBW defoliation) spruce-fir inventory projected with no harvest for moderate and severe SBW outbreaks beginning in 2010 for all of Maine. Triangle symbols denote scenarios with balsam fir (bf) defoliation levels applied to all species, and no symbols denote scenarios with reduced defoliation on spruce species relative to fir. Salvage estimates (gray lines) reflect volume of periodic mortality available for salvage harvesting.

The statewide analysis shows that SBW host species are an important component of forest stands across more than one-half of the forested area in the state and represent a merchantable standing volume of almost 5.5 billion ft^3 (155 million m^3). This resource is susceptible to substantial SBW-induced mortality and growth loss. Forest conditions and the management context in Maine have changed considerably since the 1970–1980s SBW outbreak, limiting the ability to infer future impacts from past experience. These changes make integration of the SBWDSS with forest modeling an important and powerful approach to understanding the potential threat of future outbreaks and providing possibilities for mitigating that threat through proactive management. Based on our results with the two test townships and statewide FIA impact analysis, there would be a clear benefit to forestland owners and managers across Maine from conducting a spatially explicit township-by-township analysis of potential SBW impacts in preparation for the next SBW outbreak.

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