Evaluating the interacting effects of forest management practices and periodic spruce budworm infestation on broad-scale, long-term forest productivity

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- We used the forest landscape model LANDIS-II to simulate interactions and effects of timber harvesting and spruce budworm outbreaks on future forest conditions (2010-2110) across 10 million acres of commercial forestland in Maine
- Projections suggest that many areas that did not support balsam fir and spruce *sp.* in 2010 will transition to a more mixed composition with a significant budworm host component in the next 50 years, and that the combination of natural mortality and salvage harvesting during the next outbreak(s) will exacerbate the background trend towards decreasing spruce-fir forest area.

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http://www.nsrcforest.org

Project Summary:

The sustainable management of forests requires a clear understanding of the cumulative effects of anthropogenic and natural disturbance over large spatial scales and long time horizons. In the Northern Forest, timber harvesting is the primary disturbance agent, but insect outbreaks can also be an additional, critical agent of disturbance that influences and can also interact with forest management. Due to host-specificity, the disturbance dynamics of insect outbreaks are closely coupled to the distribution of their host species; thus, changes in forest composition and age resulting from timber harvesting can influence the development, duration, and intensity of an outbreak (e.g., Radeloff et al. 2000). In addition to this indirect interaction, the decisions of land owners to salvage harvest during an outbreak to capture value that would otherwise be lost to insect-induced mortality (Foster and Orwig 2006) can drastically alter forest structure and have lasting effects on the vulnerability of a landscape to future outbreaks.

We used a forest landscape model, LANDIS-II (LANDscape DIsturbance and Succession), to simulate the coupled dynamics of forest management and periodic outbreaks of the eastern spruce budworm (*Choristoneura fumiferana* (Clem.)) across a 10 million acre study area in northern Maine. This native pest of the northeastern U.S. and eastern Canada has historically infested these regions every 30 to 50 years, causing widespread defoliation, growth reduction, and mortality of balsam fir (*Abies balsamea*) and spruce (*Picea spp.*) trees (MacLean 1980, Irland et al. 1988). Apparent increases in outbreak extent, synchronicity, and severity throughout the 20th century have fueled decades of debate concerning the influence of forest management practices on budworm disturbance dynamics, and we designed scenarios to provide a better understanding of how harvesting, salvage, and budworm outbreaks interact and influence forest dynamics and wood supply.

Our projections suggest that the spread and increasing dominance of balsam fir, the primary host species for budworm, will drive changes in landscape vulnerability to infestation. Many areas in northern Maine that did not support balsam fir and spruce *sp.* in 2010 may transition to a more mixed composition with a significant host component by 2050. Following a spruce budworm outbreak, the combination of budworm-induced mortality and salvage will cause a short-term 15-30% (depending on timing and outbreak severity) decline in spruce-fir biomass. Spruce-fir forest will recover in many disturbed or salvaged areas but not all as successional dynamics drive forest type conversion in other areas.

Background and Justification:

Repeated spruce budworm infestations have profoundly influenced Maine's spruce/fir forest. Well documented outbreaks resulting in widespread mortality occurred ca. 1913-19 and 1972-86 (a third outbreak in the 1940s caused non-lethal defoliation) (Irland et al. 1988, Seymour 1992). The most recent outbreak stimulated a spray protection program which at its peak treated several million acres annually. Severe mortality motivated extensive pre-salvage and salvage harvests that typically took the form of commercial clearcuts (Irland et al. 1988). Budworm-induced mortality and salvage cutting well above recognized long-term allowable levels converted large blocks of forest to an early-successional stage. As Maine anticipates the next outbreak, these areas are younger, more vigorous, and less vulnerable than they were prior to the last outbreak. However, greater than 2 million acres consist of vulnerable poletimber and sawtimber (McWilliams et al. 2005).

Changes in forest conditions and management context limit our ability to infer the impact of future budworm outbreaks from past experience. Logging and natural disturbance since the last outbreak have generally favored the recruitment of fir, the most vulnerable host species, but a decline in the use of herbicide to tend softwood regeneration in commercial clearcuts and the selective removal of spruce and fir from the overstory of many formerly mixedwood stands may lessen future forest vulnerability (Seymour 1992, McWilliams et al. 2005). Improved road networks and developing markets will presumably provide a greater range of management options for the mitigation of budworm impact then were available in the 1970s and 1980s, but clearcut regulations, social pressures, and ecological realities may have the opposite effect. Moreover, Maine's formerly industrial forest is now owned by a diverse set of entities including investment firms, logging contractors, developers, high net-worth individuals, and conservation groups (Hagan et al. 2005). How these new landowners collectively respond to the next budworm outbreak will in large part determine the future condition of the spruce/fir forest. Thus it is critical that we develop methods to anticipate and address the sustainability challenges presented by large-scale natural disturbance coupled with changing forest management practices, ownership, public policy, and market conditions.

Background and Justification:

Landscape simulation has become an essential tool for understanding the long-term effects of land-use activities across large areas. Spatially explicit simulations of forest disturbance and succession provide information about future forest conditions critical to evaluating interactions between resource management and ecosystem process. Because forest succession and insect outbreaks operate at different spatial and temporal and scales (i.e., succession is a relatively slow process compared to an insect outbreak), understanding their coupled dynamics requires a multi-scale forest landscape model such as LANDIS-II (LANDscape DIsturbance and Succession) (Scheller et al. 2007). Recent model updates allow users to simultaneously model disturbances with different spatiotemporal behavior. Further, a module designed specifically to model insect outbreaks has been developed and also parameterized for simulating outbreaks of the eastern spruce budworm (Sturtevant et al. 2004).

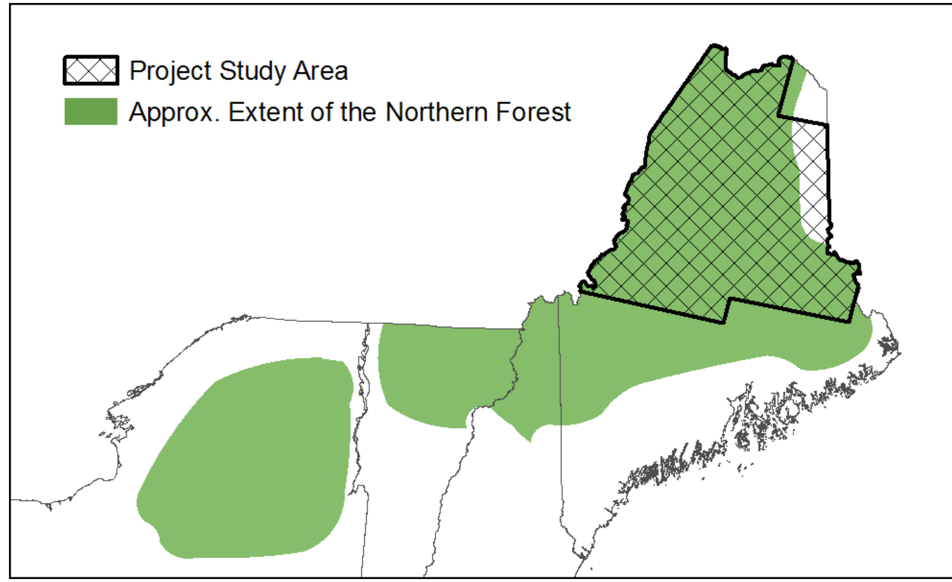

Figure 1. Study area encompassed approximately10 million acres of commercial forestlands in Maine and the Northern Forest.

The goal of our project was to use landscape simulation to provide a better understanding of the combined impact of forest management practices and spruce budworm outbreaks on forest-level productivity over large areas and long time periods. Our objectives were to: 1) map current forest conditions including composition, age structure, and budworm vulnerability across 10 million acres of commercial forestland in Maine (Figure 1); 2) calibrate the forest landscape model LANDIS-II to northeastern tree species assemblages and current conditions; 3) develop models of contemporary and alternative forest management practices designed to broadly evaluate interactions between management activities and budworm disturbance; and 4) simulate future (2010-2110) forest conditions resulting from forest management and spruce budworm infestation, and evaluate the future status of broad-scale forest productivity and budworm vulnerability.

Methods:

Within LANDIS-II, a forest is represented by a grid of interacting cells, and conditions within each cell are identified by tree species and forest age (Figure 2). We modeled 13 ecologically and economically important hardwood and softwood species. We produced maps of percent biomass using methods developed in a companion study (Sader et al. 2013 *Unpublished Report*[1]) to identify the three most abundant species for each cell, and assigned cohorts based on relative species abundance. We assigned age to each cell using a combination of a Landsat satellite imagery and U.S. Forest Inventory and Analysis (FIA) data made available through a collaborative agreement[2]. Cells that had received a stand-replacing disturbance 1970-2010 (Sader et al. 2013[1]) were assigned age based on time since disturbance. For the remaining cells, age was assigned randomly to contiguous cell neighborhoods based on the distribution of stand age for mature FIA plots (50 –150 years old).

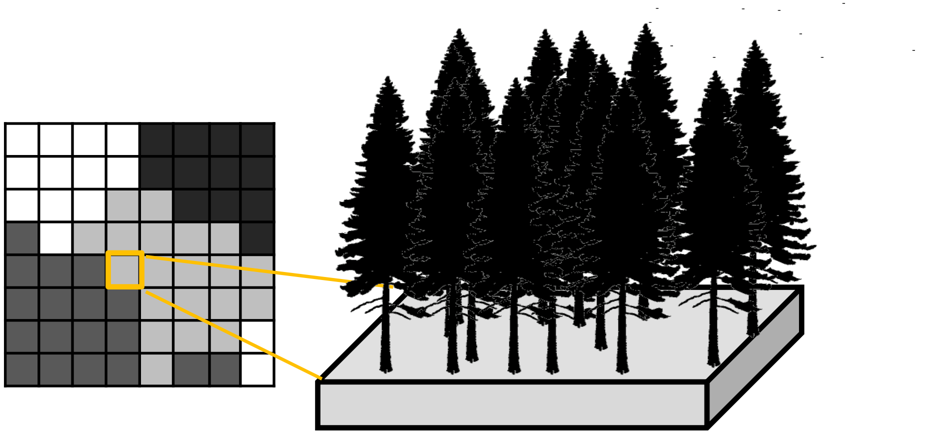

Figure 2.Example of the cell-based system used by LANDIS-II to represent a single species (Red Spruce) even-aged (100 year old) area of forest. Conditions within each cell are assumed to be homogenous.

Within LANDIS-II, the accumulation of live aboveground biomass for each cohort is modeled as a function of age, species' maximum annual net primary productivity ($ANPP_{max}$), and maximum aboveground biomass (B_{max}) (Scheller et al. 2004). Both $ANPP_{max}$ and B_{max} can be varied to reflect species' response to ecoregional variability in environmental conditions. We divided our study into 6 ecoregional types based on climate and site conditions and used the process model PnET-II (Aber et al. 1995) to estimate $ANPP_{max}$ for each ecoregion (Table 1) in a manner similar to Ravenscroft et al. (2010). Like $ANPP_{max}$, the probability that a species will establish at a site (P_{est}) varies based on a combination of species traits and environmental conditions. We estimated P_{est} for each species by comparing the number of FIA plots (2004-2008) with seedlings to the number of plots with seedlings and 1" saplings within our study area (Figure 2).

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[1] http://nsrcforest.org/project/using-satellite-imagery-map-forest-vulnerability-spruce-budworm-outbreaks

[2] USFS Northern Research Station, FS Agreement No. 11-MU-11242305-035

Methods:

We used the Biological Disturbance Agent (BDA) extension to LANDIS-II (Sturtevant et al. 2004) to emulate spruce budworm dynamics in Maine. Within the BDA, disturbance is probabilistic and the probability of disturbance for any given cell is governed by the presence of host species and the relative influence of cohort age on vulnerability (if applicable). Additional factors (e.g., abundance of host in the surrounding neighborhood) that may have an effect can be used to modify site vulnerability. If a cell is disturbed, mortality is species- and cohort-specific. Spruce budworm host species (i.e., balsam fir and red, white, and black spruce) were included in the 13 species for which percent species biomass was mapped (Figure 3; Sader et al. 2013[1]), and in our map of species-age cohorts. We assumed the same host relationships as Hennigar et al. (2008). The temporal pattern of outbreaks is controlled using a uniform or random function describing the outbreak interval and potential range of outbreak intensities. We used a random function with a mean outbreak interval of 67 years (SD = 27 years) (Fraver et al. 2007).

We used the Biomass Harvest extension to LANDIS-II (Gustafson et al. 2000) to emulate the recent forest management regime in Maine, which is characterized by limited clearcutting and extensive partial harvesting. Management units were based on ownership circa 2010, encompassing 1040 parcels and >80 owners. We estimated the harvest rate ca. 2000-2010 for all owners within our study area using satellite-derived disturbance information (Sader et al. 2013[1]) and projected those rates in our baseline scenario using two harvest prescriptions: a clearcut harvest and a partial harvest designed to remove 50% of the biomass of a stand via group selection. We assigned the clearcut rate for each owner based on their rate of stand-replacing harvest, assuming an average 4% clearcut rate across owners following recent statewide trends.

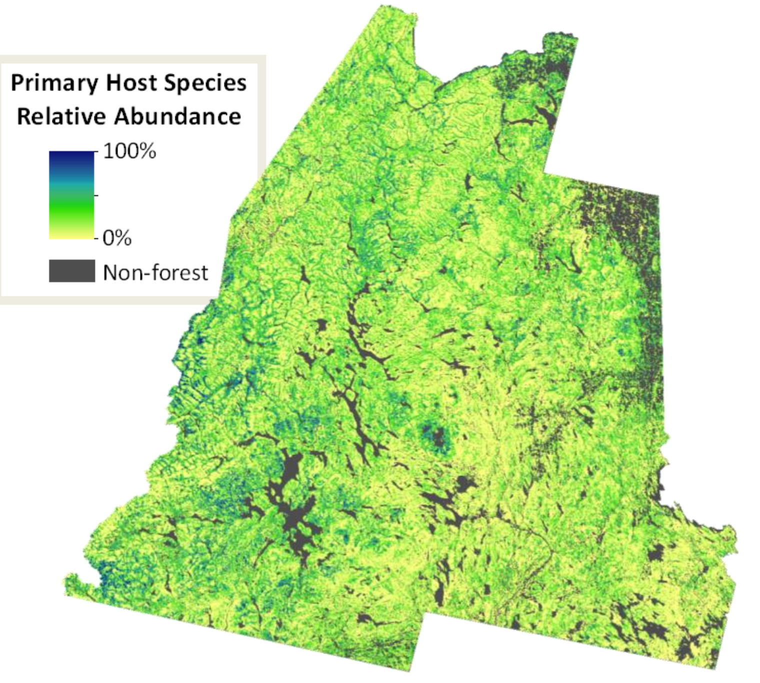

Figure 3. Map of the relative abundance of primary host species for the eastern spruce budworm (balsam fir and white spruce) for our study area. Adapted from Sader et al (2013 ; *Unpublished Report*[1]).

Methods:

In addition to the business-as-usual management reflected in our baseline scenario, we also designed scenarios to simulate a return to more intensive management as was occurring in Maine ca. 1985-1995. The Maine Forest Practices act was passed in 1989 and management in the years leading up to and just after implementation included a greater proportion of harvested acreage via clearcut and a smaller total harvest footprint. We adjusted the clearcut and partial harvest rates of the baseline scenario to reflect an increase in the proportion of total harvest by clearcut from 4 to 40% on average across the landowners, while controlling for the tradeoff between volume and area harvested when comparing partial and clearcut harvests. In general, the area of a partial harvest must be 2-3 times larger than a clearcut harvest in order to achieve the same volume removed. This strategy ensured that differences between scenarios could be attributed to the effects of harvest area and intensity and not differences in volume removed. We simulated each harvest scenario with BDA multiple times.

Prior to our research there was no linkage between the Biomass Harvest and BDA extensions of LANDIS-II, so it was not possible to simulate salvage harvesting. Through an affiliated project[2], we collaborated with LANDIS-II developers to build a coupled version of the Biomass Harvest and BDA modules in which the presence of an outbreak can be used to trigger implementation of harvest prescriptions. We used this new capability to simulate salvage harvesting during outbreak intervals. We assumed that all landowners would attempt to salvage in areas of high vulnerability, and that salvage harvesting would increase harvest rates by 20-30% (Maine Forest Service 2001).

We quantified changes and uncertainty associated with total and host species biomass. We also classified forestland within our study area based on risk of infestation by spruce budworm (Table 1) using a modified version of the stand impact matrix developed by Hennigar et al. (2011) and evaluated projected trends under current and past management regimes.

Table 1. Definitions of risk classes used to classify forestland.

Class	Total Host Species Relative Abundance	Primary Host Species Abundance (as proportion of Total Host)
FWRB	75-100%	50-100%
RBFW	75-100%	0-50%
FWMX	10-75%	50-100%
RBMX	10-75%	0 -50%
Non-host	0-10%	

[2]NASA-NIFA Carbon Cycle Science 2010. "Carbon Dynamics and Forest Management: A retrospective analysis and projection of the potential effects of land use, climate change, and natural disturbances in Northeastern Forests." PI A. Weiskittel.

Results:

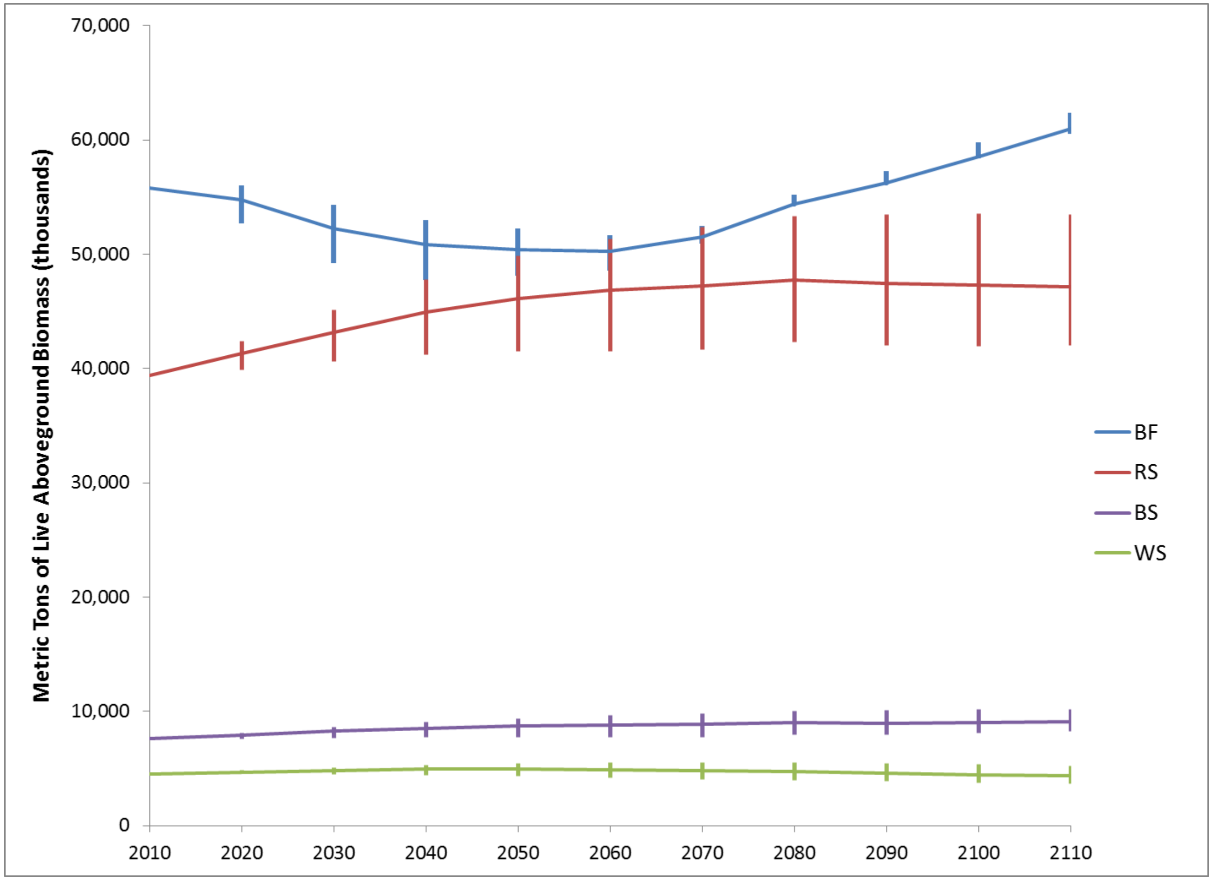

Figure 4. In the absence of a spruce budworm outbreak, our results suggest that live aboveground biomass of balsam fir (BF; blue line) will decline 2 - 5% over the next 40 years and then increase 3 - 6% each period thereafter for the next 60 years. Vertical bars represent uncertainty associated with the biomass calculations generated by year-to-year and owner-to-owner variability in harvest rates, and projections indicate that uncertainty is greatest around the future of red spruce biomass (RS; red line). If harvest rates were to trend high (vertical minimum), red spruce biomass would be expected to remain relatively stable. Alternatively, if harvest rates were to trend low then red spruce biomass would likely increase on average 2.5%. Biomass of the other host species, white spruce (WS; green line) and black spruce (BS; purple line) spruce, are not likely to change substantially over the next 100 years.

Results:

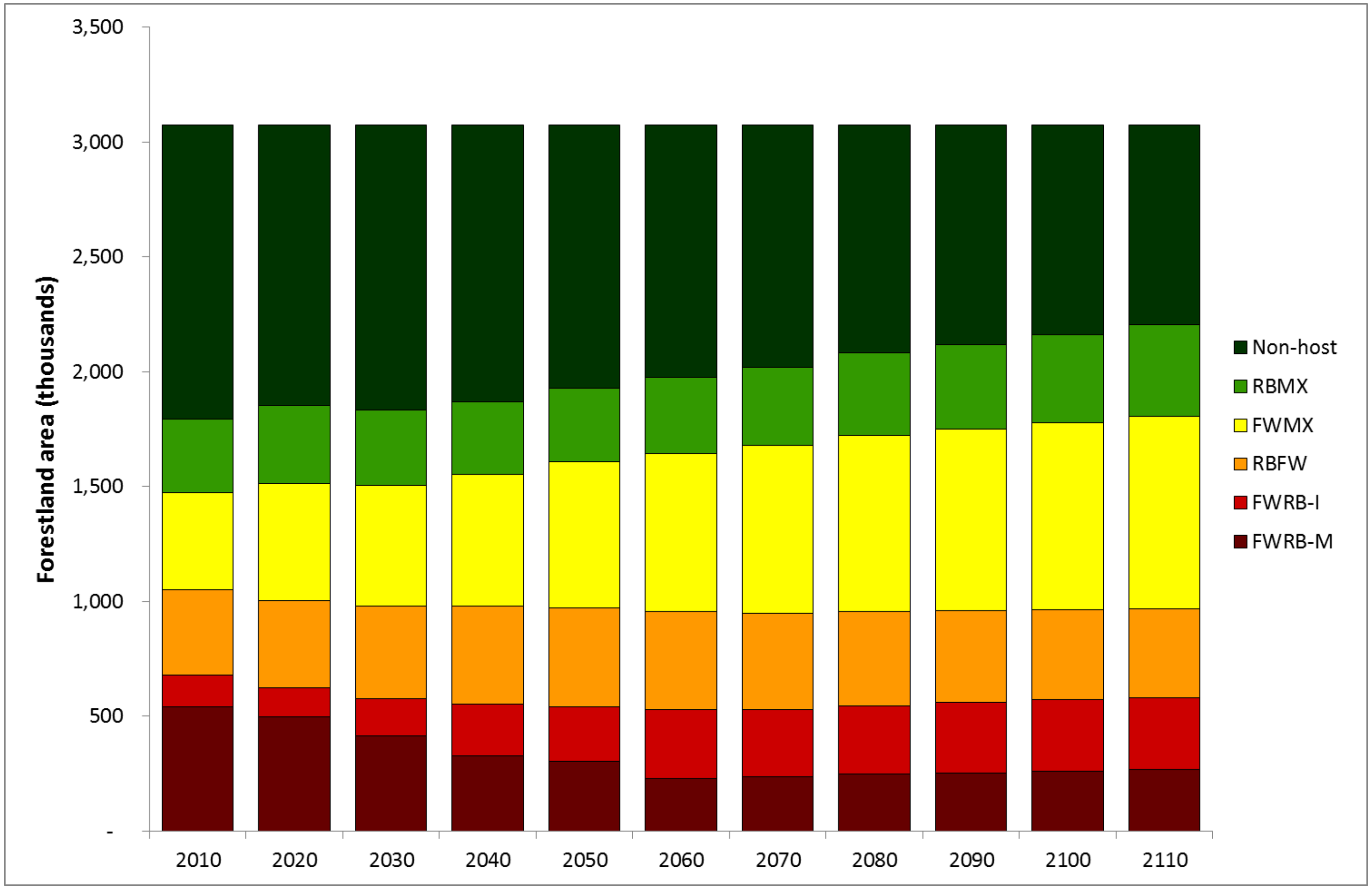

Figure 5. Changes in the abundance and age structure of balsam fir will drive changes in landscape vulnerability as defined by Hennigar et al. (2011). The amount of non-host forest (Non-host; dark green bars) will decline 32% as fir encroaches and expands in areas of mixed forest (FWMX; yellow bars) currently dominated by other species. Concurrently, in areas dominated by fir - the underlying age structure will shift as areas of mature host forest (FWRB-M; dark red bars) are replaced (via harvesting) by areas of young forest dominated by the primary host species (FWRB-I; red bars). Overall, our projections suggest that the area at high risk of infestation (FWRB-I & FWRB-M) will decline 15% but the area at medium risk of infestation (RBFW, FWMX, and RBMX) will increase 46%. Note: Median results shown.

Results:

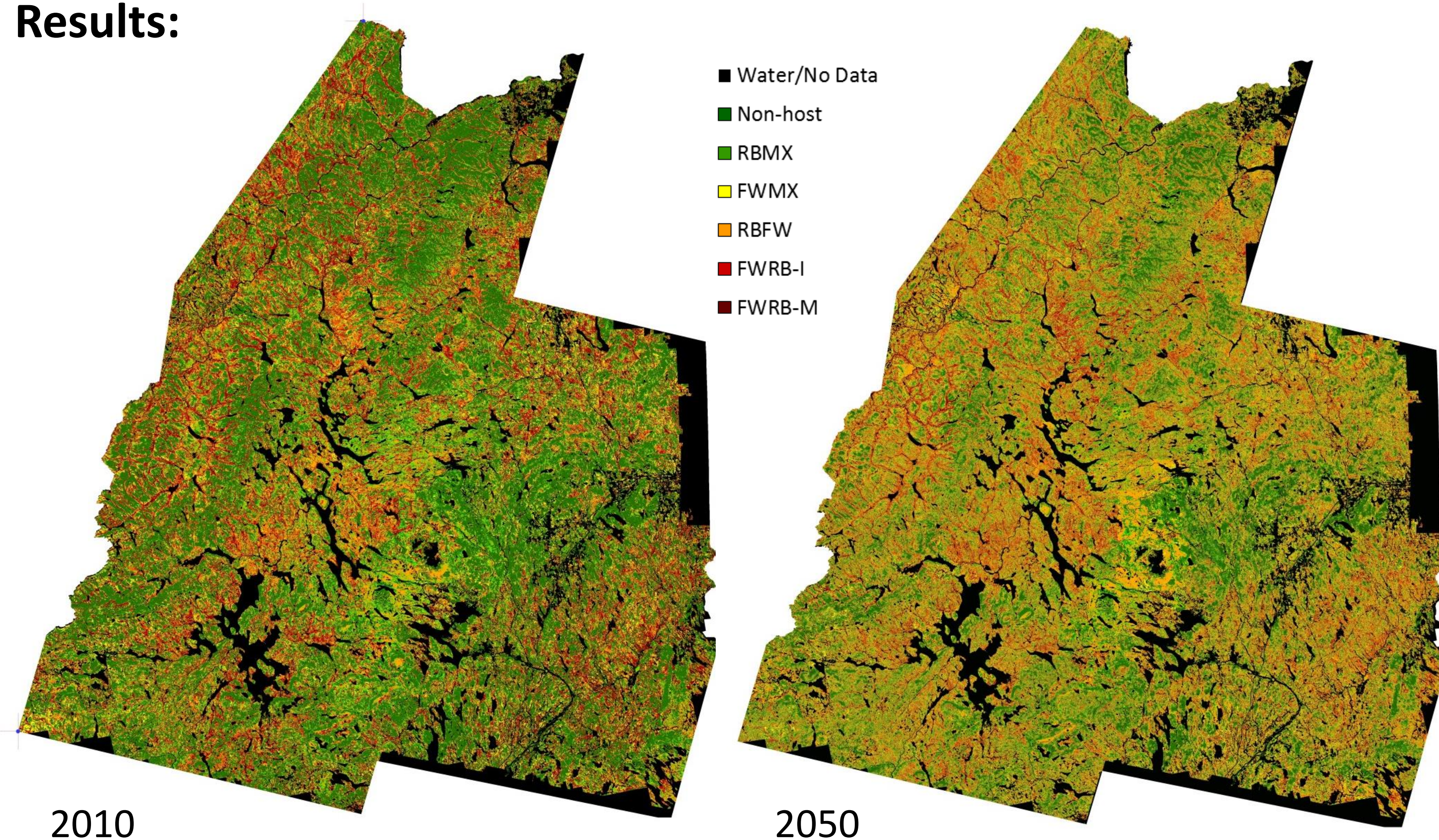

Figure 6. Circa 2010, forest with a high vulnerability to infestation by spruce budworm (FWRB-I & FWRB-M; red and dark red, respectively) was distributed broadly across our 10 million acre study area. Our projections suggest that many areas that did not support balsam fir and spruce *sp.* (Non-host; dark green) in 2010 will transition to a more mixed composition with a significant host component by 2050, primarily as a result of balsam fir expansion and increasing dominance (FWMX; yellow). Note: Median results shown.

Results:

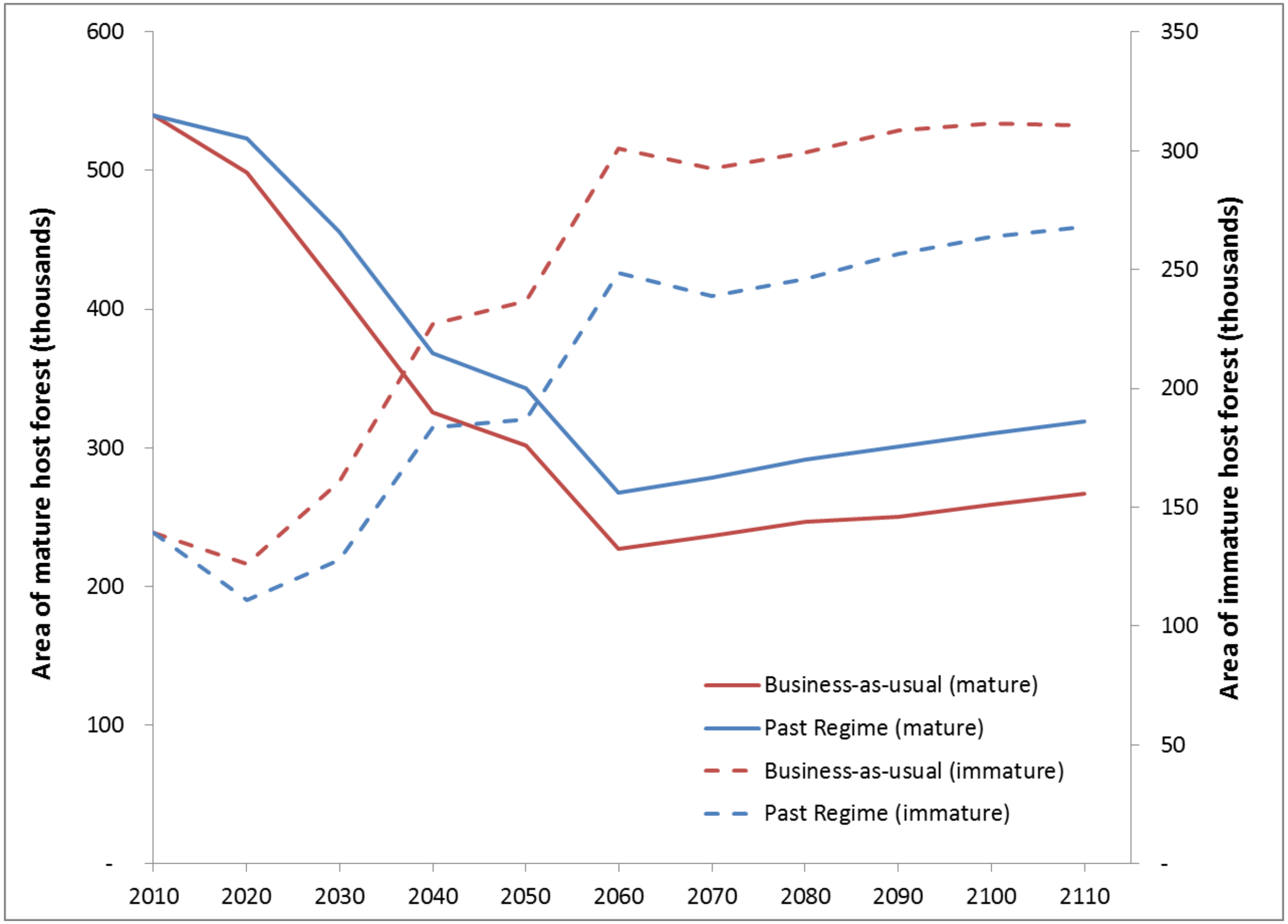

Figure 7. A shift in management towards decreased reliance on partial harvesting and increased clearcutting (blue lines) would influence the future age structure of highly-vulnerable host forest (i.e., FWRB) compared to the current harvest regime (red lines). Under either scenario, the area of immature (<40 years old) and mature FWRB forest is projected to increase and decrease, respectively. The reduced harvesting footprint that would result from more volume being removed via clearcutting would have the duel effects of 1) increasing current risk by leaving more mature host forest intact (solid lines), while also 2) decreasing future risk by establishing fewer new cohorts of immature host forest (dashed lines).

Results:

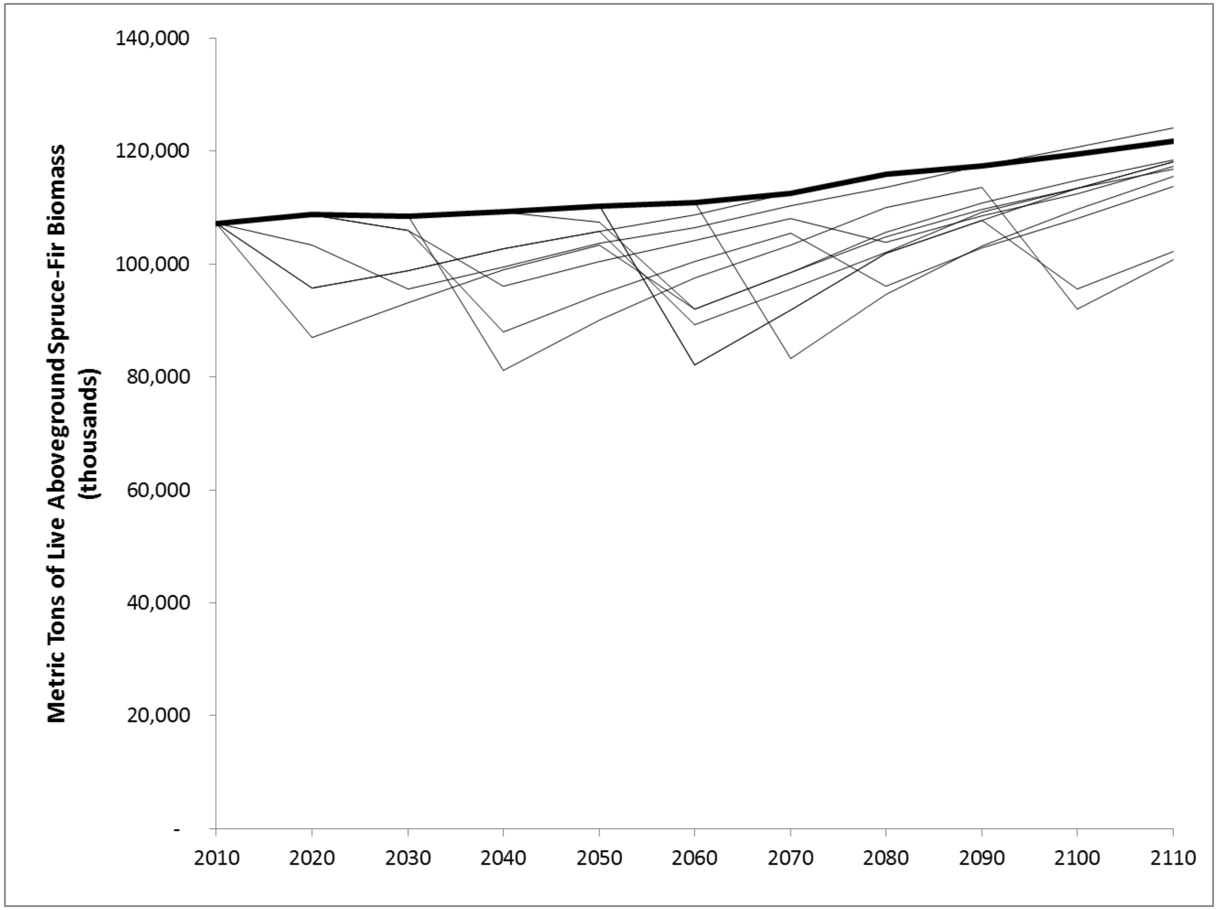

Figure 8. Under the current harvesting regime, we expect live aboveground biomass of spruce-fir to increase in the future (bold line) largely as a result of the continued establishment and growth of balsam fir. Given outbreak interval behavior in Maine (67 years ± 27 years between outbreaks; Fraver et al. 2007), the next outbreak of spruce budworm could begin as soon as within the next 10 years or as late as the 2050s. We projected multiple potential outbreak scenarios (thin lines) and our results suggest that, whenever the next outbreak(s) occurs, the combination of budworm-induced mortality and salvage harvesting will cause a 10-30% decline in spruce-fir biomass during outbreak periods compared to the current harvesting regime with no outbreaks (i.e., bold line). Outbreak periods will be followed by a long period of biomass recovery that will last 40-70 years depending on timing and outbreak severity.

Results:

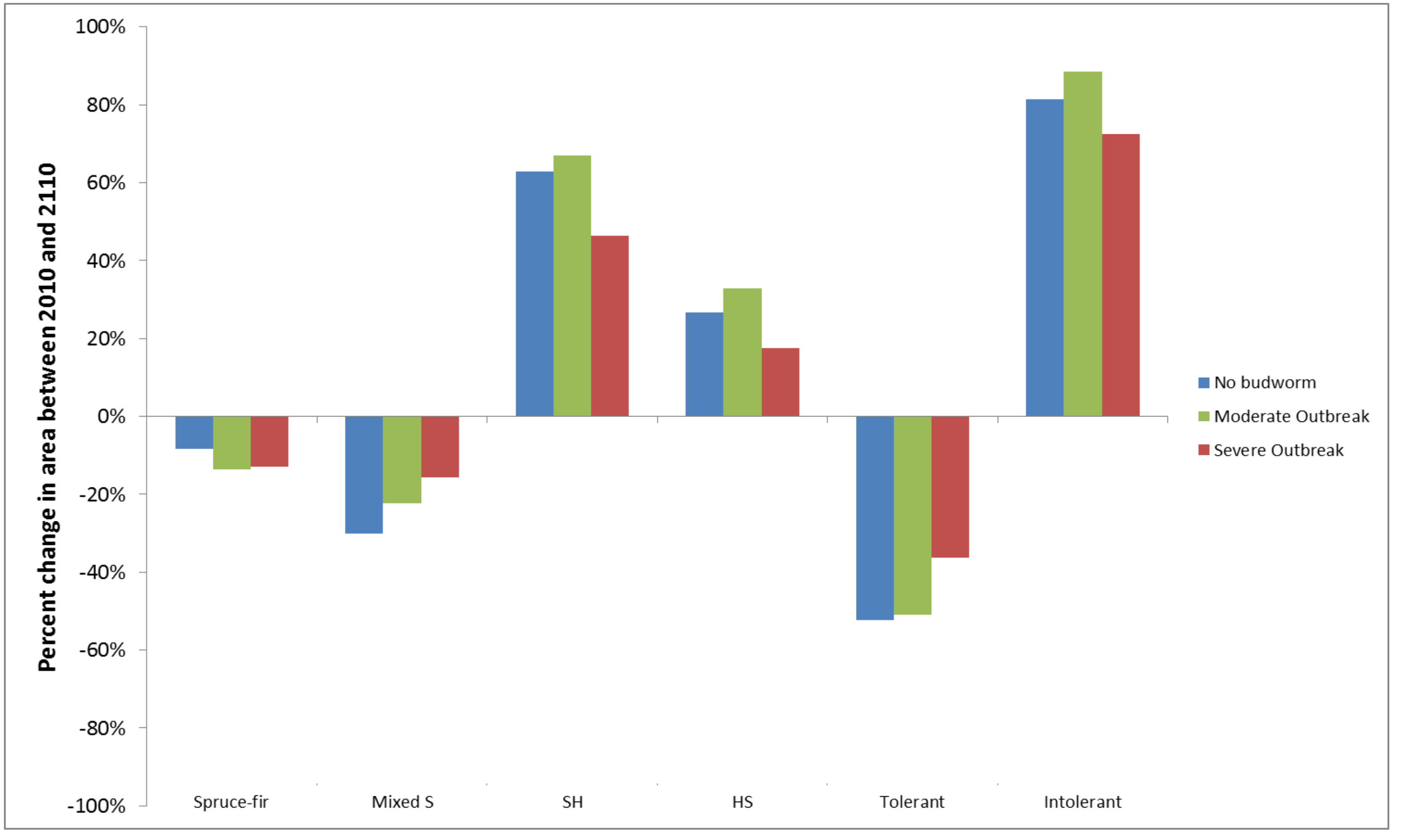

Figure 9. Our projections suggest that one of the important net effects of harvesting x budworm interactions will be a change in the magnitude of species turnover that occurs over the next 100 years. In the absence of spruce budworm (blue bars), we expect the area of softwood-dominated and tolerant hardwood forest types to decline, and the area of mixedwood forest types and forest dominated by intolerant species to increase. Assuming, as an example, that there are 2 outbreaks over the next 100 years, the combination of budworm-induced mortality and salvage harvesting will have a negative effect on the area of forest dominated by spruce-fir and a positive effect on the area of mixed-softwood forest and tolerant hardwood forest, regardless of outbreak severity (green vs. red bars). The effects on mixed forest and intolerant hardwood forest may be dependent on outbreak severity. For example, moderate outbreaks (green bars) may have a positive effect on intolerant hardwood forest, compared to the net negative effect of severe outbreaks (red bars).

Implications and applications in the Northern Forest region:

Significant changes in forest conditions, forest policy, and land ownership since the last outbreak of spruce budworm limit our ability to infer the impacts of future outbreaks from past experience. We used a forest landscape model to simulate forest management and periodic outbreaks across a 10 million acre study area in northern Maine that included more than 80 landowners to provide a better understanding of how harvesting and budworm dynamics interact and influence forest and timber supply dynamics. Data provided by FIA plots has previously shown that balsam fir was the leader in terms of both ingrowth and accretion in the early 2000s (McWilliams et al. 2005), and our projections suggest that fir dominance will increase and drive changes in landscape vulnerability leading up to the next outbreak. The amount of non-host forest will steadily decline as fir continues to encroach, leading to a >45% increase in forest types considered at medium risk to infestation by spruce budworm. Because of the intermixing with hardwoods in those areas, mortality rates are likely to be lower compared to areas dominated by host species. However, those areas could influence overall landscape vulnerability by promoting the spread of an outbreak.

In areas at high risk of infestation dominated by balsam fir/white spruce, the underlying age structure will shift over time as timber harvesting has the duel effects of removing mature trees and facilitating establishment of new cohorts of host trees, particularly fir. With a shift in management towards decreased reliance on partial harvesting and increased clearcutting, this inherent tradeoff would still exist. However, because less immature host forest would be created, that shift would potentially begin to change system dynamics by reducing the future availability of the high-vulnerability forest type for subsequent outbreaks.

The last outbreak of spruce budworm in Maine, which occurred 1973-1985, was relatively severe and the harvest of spruce-fir during the 1980s increased ~30% (Maine Forest Service 2001), contributing to a ~40% decline in the spruce-fir growing stock between 1985 and 1995 (McWilliams et al. 2005). When the next outbreak will occur is uncertain, and the magnitude of effects on the spruce-fir forest will be dependent on timing and outbreak severity. Our projections suggest that the combination of natural mortality and salvage harvesting will cause a 15-30% decline in spruce-fir biomass during the outbreak(s) followed by slow recovery. The spruce-fir forest may not, however, recover everywhere it is now present; successional dynamics in disturbed or salvaged forest will interact with background rates of species turnover that, ultimately, may lead to broad-scale and persistent forest type conversion.

Future directions:

In the future, temperatures in the Northern Forest are likely to increase and precipitation patterns are likely to change as a consequence of climate change. The implications of these changes on future species distributions have been modeled broadly, and it is expected that balsam fir and spruce will decline, while red maple will increase (Iverson et al. 2008). Projections of future species distributions have not, however, considered interactions with other disturbances such as timber harvesting. In addition, it is unclear how climate change will influence species and forest-level productivity. Under funding obtained from the NASA/USDA National Institute of Food and Agriculture (NIFA) Carbon Cycle Science program we are incorporating climatological effects into our landscape simulations. We have designed alternative scenarios that explore interactions between timber harvesting (business-as-usual), outbreaks of spruce budworm (light, moderate, and severe) and salvage harvesting, and climate change (low and high emission according to the Intergovernmental Panel on Climate Change).

After broad-scale divestiture of timberland by forest product companies in the 1990s and 2000s, investment firms are now the predominant type of private landowner throughout the US. Unlike their industrial predecessors, these new owners operate over relatively short time horizons (i.e., 5-15 years) and are willing to consider multiple means of monetizing their asset, including development and real estate sales. During the last budworm outbreak most of the affected forest area was owned and managed by a small number of large industrial owners that were able to mobilize a broad-scale salvage effort, which was later followed by intensive management to maintain forestland under softwood production. The next spruce budworm outbreak is likely to exert a strong influence on the willingness of landowners (new and old) to reconsider their land management options. Under funding obtained from the NSF Coupled-Natural Human Systems Program, we will expand our use of LANDIS-II to improve understanding of the coupled biophysical-social linkages that underpin patterns of landscape change within rural forests, and how specific linkages drive the a forest ecosystem towards a particular state that may be more or less resilient to additional disturbance.

Products:

Manuscripts in preparation or planned on the following topics:

- Calibration of LANDIS-II to Acadian forest species and dynamics (anticipated submission 4/2014)
- Evaluating interactions between policy and management on resource sustainability (anticipated submission 8/2014)

Presentations:

- Simons-Legaard, E. M., K. Legaard, A. Weiskittel, and S. Sader. 2013. Evaluating the interacting effects of forest management and spruce budworm outbreaks on broad-scale, long-term forest conditions in the Northern Forest of the northeastern U.S. Oral presentation at the Annual Meeting of the Ecological Society of America, Minneapolis, Minnesota.
- Legaard, K.R., S. Sader, J. Wilson, E. Simons-Legaard, and A. Weiskittel. 2013. A spatial assessment of vulnerability to defoliation by spruce budworm across the commercial forestland of northern Maine. Oral presentation at the New England Society of American Foresters Spring Meeting, Bethel, Maine.
- Legaard, K.R., S. Sader, J. Wilson, E. Simons-Legaard, and A. Weiskittel. 2012. Mapping vulnerability to defoliation by spruce budworm using Landsat satellite imagery and FIA field plots. Poster presented at the Eastern CANUSA Forest Science Conference, Durham, New Hampshire.
- Simons-Legaard, E., K. Legaard, J. Wilson, A. Weiskittel, and S. Sader. 2012. Long-term outcomes and tradeoffs of forest policy and management practices on the borad-scale sustainability of forest resources: wood supply, carbon, and wildlife habitat. Poster presented at the Eastern CANUSA Forest Science Conference, Durham, New Hampshire.

Grants resulting in part from the success of this project:

- NSF Coupled-Natural Human Systems, 2013: When natural disturbance meets land use change: an analysis of disturbance interactions and ecosystem resilience in the Northern Forest of New England. Lead PI E. Simons-Legaard.
- NASA/USDA National Institute of Food and Agriculture (NIFA) Carbon Cycle Science, 2010: Carbon dynamics and forest management: A retrospective analysis and projection of the potential effects of land use, climate change, and natural disturbance in northeastern forests. Lead PI A. Weiskittel.

Literature Cited:

Aber, J., S. Ollinger, C. Federer, P. Reich, M. Goulden, D. Kicklighter, J. Melillo, and R. Lathrop. 1995. Predicting the effects of climate change on water yield and forest production in the northeastern United States. Climate Research 5:207-222.

Foster, D. and D. Orwig. 2006. Preemptive and salvage harvesting of New England forests: when doing nothing is a viable alternative. Conservation Biology 20:959-970.

Fraver, S., R. Seymour, J. Speer, and A. White. 2007. Dendrochronological reconstruction of spruce budworm outbreaks in northern Maine, USA. Canadian Journal of Forest Research 37:523-529.

Gustafson, E., S. Shifley, D. Mladenoff, K. Nimerfro, and H. He. 2000. Spatial simulation of forest succession and timber harvesting using LANDIS. Canadian Journal of Forest Research 30:32-43.

Hagan, J., L. Irland, and A. Whitman. 2005. Changing timberland ownership in the Northern Forest and implications for biodiversity. Manomet Center for Conservation Sciences Report #MCCS-FCP-2005-1, Brunswick, Maine, USA.

Hennigar, C., D. MacLean, D. Quiring, and J. Kershaw. 2008. Differences in spruce budworm defoliation among balsam fir and white, red, and black spruce. Forest Science 54: 158-166.

Hennigar, C., J. Wilson, D. MacLean, and R. Wagner. 2011. Applying a Spruce Budworm Decision Support System to Maine: projecting spruce-fir volume impacts under alternative management and outbreak scenarios. Journal of Forestry 109:332-342.

Irland, L., J. Dimond, J. Stone, J. Falk, and E. Baum. 1988. The spruce budworm outbreak in Maine in the 1970's - assessment and future directions for the future. University of Maine Agricultural Experiment Station Bulletin 819. 119 pp.

Iverson, L.R., Prasad, A.M., Matthews, S.N., Peters, M., 2008. Estimating potential habitat for 134 eastern US tree species under six climate scenarios. Forest Ecology and Management 254, 390-406.

Maine Forest Service. 2001. 2000 Wood processor report. Maine Forest Service, Department of Conservation, Augusta, Maine, USA.

MacLean, D. 1980. Vulnerability of fir-spruce stands during uncontrolled spruce budworm outbreaks: a review and discussion. Forestry Chronicle 56:213-221.

McWilliams, W., B. Butler, L. Caldwell, D. Griffith, M. Hoppus, K. Laustsen, A. Lister, T. Lister, J. Metzler, R. Morin, S. Sader, L. Stewart, J. Steinman, J. Westfall, D. Williams, A. Whitman, and C. Woodall. 2005. The forests of Maine: 2003. In, Resource Bulletin NE-164. U.S. Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA, p. 188.

Radeloff, V. , D. Mladenoff, and M. Boyce. 2000. Effects of interacting disturbances on landscape patterns: budworm defoliation and salvage logging. Ecological Applications 10:233-247.

Ravenscroft, C., R. Scheller, D. Mladenoff, and M. White. 2010. Forest restoration in a mixed-ownership landscape under climate change. Ecological Applications 20:327-346.

Scheller, R. and D. Mladenoff. 2004. A forest growth and biomass module for a landscape simulation model, LANDIS,: design, validation, and application. Ecological Modelling 180:211-229.

Scheller, R., J. Domingo, B. Sturtevant, J. Williams, A. Rudy, E. Gustafson, and D. Mladenoff. 2007. Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. Ecological Modelling 201:409-419.

Seymour, R. S. 1992. The red spruce-balsam fir forest of Maine: evolution of silvicultural practice in response to stand development patterns and disturbances. Pages 217-244 *In*: Kelty, M. J., B. C. Larson, and C. D. Oliver (Editors.), The ecology and silviculture of mixed-species forests. Kluwer Publishers, Norwell, Massachusetts. USA.

Sturtevant, B. R., E. J. Gustafson, and H. S. He. 2004. Modeling biological disturbances in LANDIS: a module description and demonstration using spruce budworm. Ecological modeling 180:153-174.