Future distribution and productivity of spruce-fir forests under climate change

Principal Investigator:

Erin Simons-Legaard, School of Forest Resources, 5755 Nutting Hall, University of Maine, Orono, ME 04469-5755, erin.simons@maine.edu

Co-Principal Investigators:

Anthony D'Amato, Rubenstein School of Environment and Natural Resources, University of Vermont, anothony.damato@uvm.edu

Kasey Legaard, School of Forest Resources, University of Maine, kasey.legaard@maine.edu

Brian Sturtevant, U.S. Forest Service, Northern Research Station, bsturtevant@fs.fed.us

Aaron Weiskittel, School of Forest Resources, University of Maine, aaron.weiskittel@maine.edu

Collaborators:

Phil Radtke, Virginia Tech

Nick Crookston, U.S. Forest Service

Shawn Fraver, University of Maine

Completion Date: June 30, 2016

- Climate envelope models that do not consider local variations in environmental conditions may overstress the effects of climate change on spruce-fir forest in the Northeast over the next century.
- Timber harvesting had a larger effect on our projections of future forest composition than climate change in northern Maine, where even with interactions between harvesting and climate change ecosystem resilience will likely ensure the distribution of spruce-fir forest remain largely unchanged over at least the next 50 years.

Funding support for this project was provided by the Northeastern States Research Cooperative (NSRC), a partnership of Northern Forest states (New Hampshire, Vermont, Maine, and New York), in coordination with the USDA Forest Service. http://www.nsrcforest.org

Project Summary

Rationale: Already at its southern range limit, the ecologically- and economically-important eastern spruce-fir forests are expected to be highly susceptible to the negative effects of climate change. Predictions based on coarse-scale climate envelope models suggest that suitable climate conditions for balsam fir and spruce *sp*. will be eliminated throughout much of their current range in the U.S. Such predictions, however, necessarily overlook the influence of fine-scale variation in environmental conditions that may allow for local persistence and important interactions with other disturbance agents (e.g., land use).

Methods: We used bioclimatic envelope models and a forest landscape model to improve understanding of how climate change will impact spruce-fir forest directly and indirectly. Within this framework, moderate resolution (30 meter) projections of species distributions and productivity under varying climate and simulations of future forest dynamics responding to different disturbance regimes (including climate change, timber harvesting, and spruce budworm) allowed for an evaluation of system sensitivity to disturbance, as well as identification of areas of potential climate refugia.

Major findings: Selection of important variables in the bioclimatic models was similar for all species, indicating that areas which are snowier and colder in winter than average characterize suitable habitat for balsam fir and spruce *sp*. (black, red, and white). Maps based on projected climate change suggest that although suitable climate conditions will decline as a result of less snow and warmer winter temperatures, patches of suitability will remain in the Northeast ca. 2090 for all but white spruce. Forest landscape projections further suggest that without a significant increase in the "natural mortality" of mature fir and spruce trees due to climate change (e.g., via thermal stress), ecosystem resilience will likely ensure the distribution of spruce-fir forest in Maine remain largely unchanged over at least the next 50 years.

Implications for the Northern Forest region: Coarse-scale climate envelope models may overstress the effects of climate change on spruce-fir forest in the Northeast over the next century. In our study, timber harvesting had a larger effect on future forest composition than climate change in Maine.

Background and Justification

- Eastern spruce-fir forests currently cover approximately 5.3 million hectares in the continental U.S., extending across large portions of the Northeast, Upper Midwest and Great Lakes, and Appalachian regions (Fig. 1).

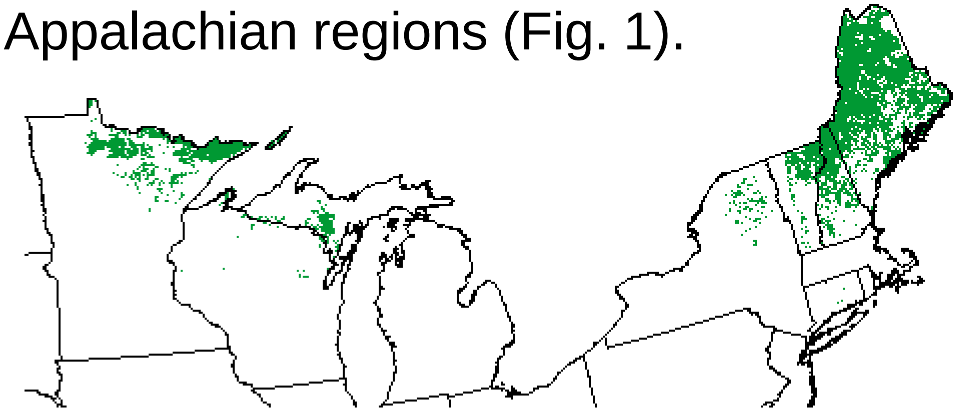


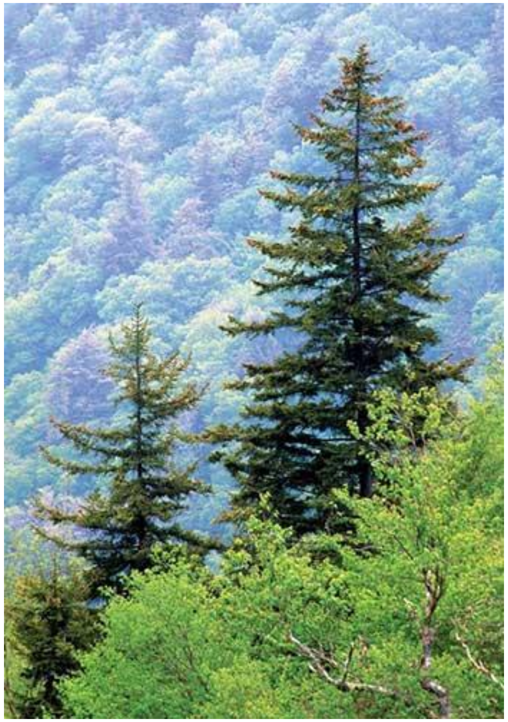
Fig 1. Distribution of the spruce-fir forest type group. Photo credit: US Forest Service, Northern Global Change Research Program (https://www.fs.fed.us/ne/global/index.html)

- The majority of these forests occur on privately-owned timberland, areas that represent high commercial and ecological importance.
- In Maine, for example, the spruce-fir forest type contains 25% of the net merchantable value (McCaskill and McWilliams 2012), and supports a number of wildlife species of regional or global conservation concern (e.g., Canada lynx; Fig. 2).

Fig. 2. Canada lynx. Photo credit: USFWS digital library

Background and Justification

- Broad-scale climate-envelope models (e.g., Iverson et al. 2007) suggest that increasing temperatures and changing patterns of precipitation will reduce the habitat suitability for the primary trees species of the spruce-fir forest type in the U.S.
- Remnant trees will also likely experience increased drought and thermal stress.
- As suitable growing conditions for fir and spruce trees are reduced or eliminated, growth and regeneration of hardwoods (e.g., maple *sp*.) or more southerly conifers are expected to be favored.
- Red spruce is currently listed as one of the top 10 of species expected to be impacted most by climate change in eastern North American, and balsam fir is expected to lose a significant portion of its current range (~15%; Potter et al. 2012).



Red Spruce. Credit: USDA Forest Service Southern Research Station Archive, Bugwood.org.

Background and Justification

- Despite the importance of spruce-fir forests, projections of future forest distribution or productivity have largely been limited to coarse climate envelope models that overlook the effects of variations in physiographic conditions (e.g., slope and aspect), which may allow for local persistence of suitable habitat in a changing climate.
- Further, interactions between climate change and other natural (e.g., forest insects) or anthropogenic (e.g., land use) disturbances have been ignored.
- Of particular importance to predicting the future of spruce-fir forests is eastern spruce budworm, which periodically (approximately every 30-60 years) causes widespread defoliation and mortality of fir and spruce trees (Fig. 3).

Fig 3. Forest damaged by eastern spruce budworm (inset). Photo Credits: Natural Resources Canada

Methods - Tree species distributions

- To better model suitable habitat conditions for balsam fir and spruce sp., we assembled an extensive database of forest inventory plots, consisting of more than 10 million observations (Fig. 4).

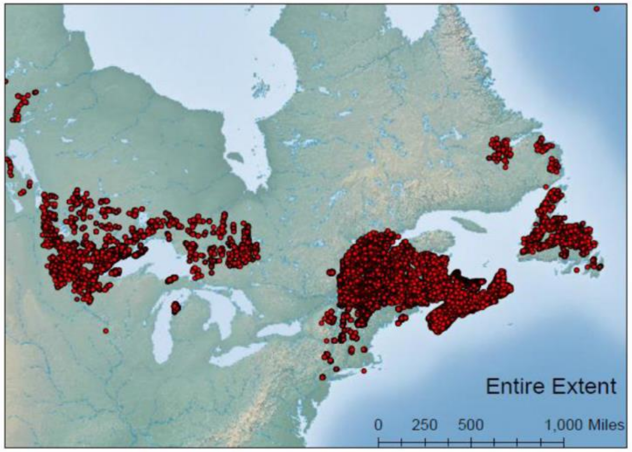


Fig 4. Locations of forest inventory plots compiled from the Northeast (Maine, Vermont, New Hampshire), the Great Lakes (Michigan, Wisconsin, Minnesota), and Canada (Ontario, Quebec, New Brunswick, Nova Scotia, Prince Edward Island) used to model suitable habitat conditions for balsam fir, black spruce, red spruce, or white spruce. Data were collected from multiple private, federal, state, and Canadian provincial agencies in order to ensure model captured the full range of environmental conditions associated with each species.

- Plot data were used to develop downscaled bioclimatic envelope models linking species data (e.g., presence/absence, basal area, stem density) with climate and topographic variables based on the Random Forest algorithm.
- Envelope models were used to map the current distribution of suitable habitat conditions for each species and to produce moderate resolution projections (30m^2) of future (2030, 2060 & 2090) distributions under the ENSEMBLE RC6 climate model.

Methods - Tree species sensitivity

- We used the LANDIS-II forest landscape model (Scheller et al. 2007) to evaluate the sensitivity of projected species distributions to interactions between climate change and landscape disturbances (i.e., timber harvesting and spruce budworm) across northern Maine (Fig 5).

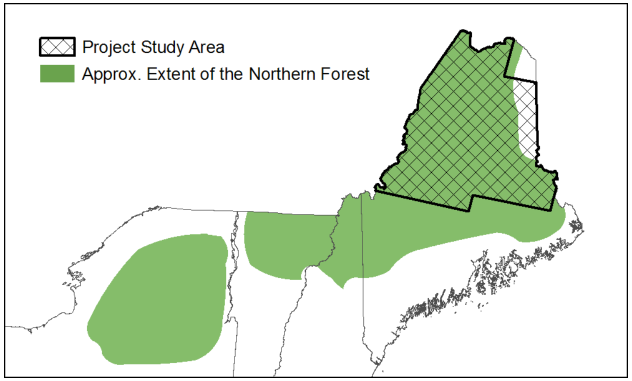


Fig 5. Study area encompassed approximately10 million acres of commercial forestlands in Maine.

- Unlike the bioclimatic envelope approach, which focuses on the suitability of climate conditions, LANDIS-II simulates local disturbance and succession dynamics using a cell-based system (Fig 6).

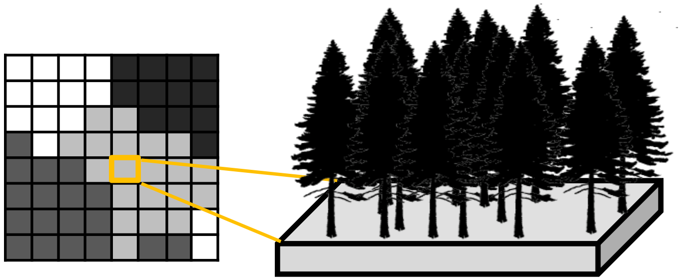


Fig 6. Example of the cell-based system used by the forest landscape model LANDIS-II to simulate local forest dynamics. Cells are typically 30 m^2 and a forest stand is composed of many cells.

Methods - Tree species sensitivity

- Cells were populated with the 1-3 most abundant tree species based on maps of percent aboveground live biomass for 13 of Maine's economically and ecologically important species developed in a companion study (Sader et al. 2013 *NSRC Report*[1]).
- We used the Biomass Succession extension (Scheller & Mladenoff 2004) to model succession, the Biomass Harvest extension (Gustafson et al. 2000) to model timber harvesting, and the spruce budworm variant of the Biological Disturbance Agent extension (Sturtevant et al. 2008) to model the effects of a spruce budworm outbreak.
- We used PnET-II (Aber et al. 1995) to estimate changes in annual net primary productivity based on downscaled projections of maximum temperature, minimum temperature and precipitation under a low-emission scenario (RCP 2.6) using the Hadley global environment model v-2 earth system (HADGE) global circulation model.

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

Results - Tree species distributions

- Balsam fir, white spruce, black spruce, and red spruce were located in 15.4%, 6.6%, 9.1%, and 4.1% of plots, respectively.
- Species occurrence models yielded excellent statistical results, as measured by area under the operating curve (AUC), with AUC > 0.90 for all species.
- Likelihood of occurrence maps revealed strong correspondence with patterns of basal area concentration (Fig 7).
- Abundance models performed well, but not as well as occurrence models, with white spruce being the most difficult to predict (R^2 65-68%) and black spruce models being consistently the most accurate (R^2 87-88%).

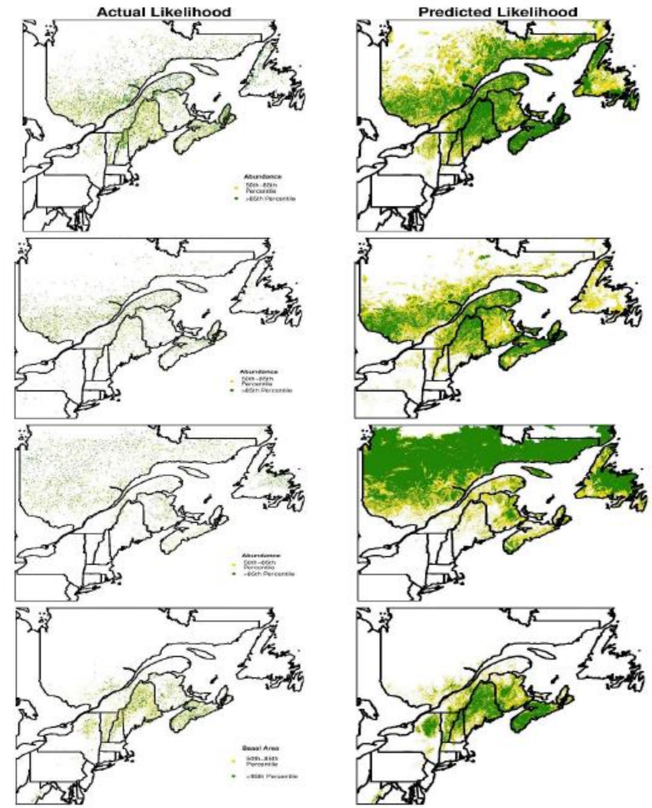


Figure 7. Actual and predicted likelihood for (a) balsam fir, (b) white spruce, (c) black spruce, and (d) red spruce. The actual likelihood represents observed plot-level basal area displayed for plots in the 85th percentile (green) and the 50th to 85th (yellow). Predicted likelihood represents a likelihood of >85% (green) or 50-85% (yellow). Adapted from Andrews (2015).

Results - Tree species distributions

- Selection of important predictor variables was similar in the occurrence and abundance models, and indicated that areas where 1) winter precipitation is equal to or exceeds growing season precipitation and 2) mean temperature in the coldest month is lower than the region-wide average characterize suitable habitat for balsam fir and spruce *sp*. (black, red, and white).
- Maps based on projected climate change (Fig 8) suggest that suitable habitat conditions for white and black spruce will disappear from the U.S. by 2060 and from the Acadian Forest Region by 2090, but patches of suitability will remain for fir and red spruce in areas of higher altitude.
- Suitable conditions for fir and white and red spruce will likely expand north.

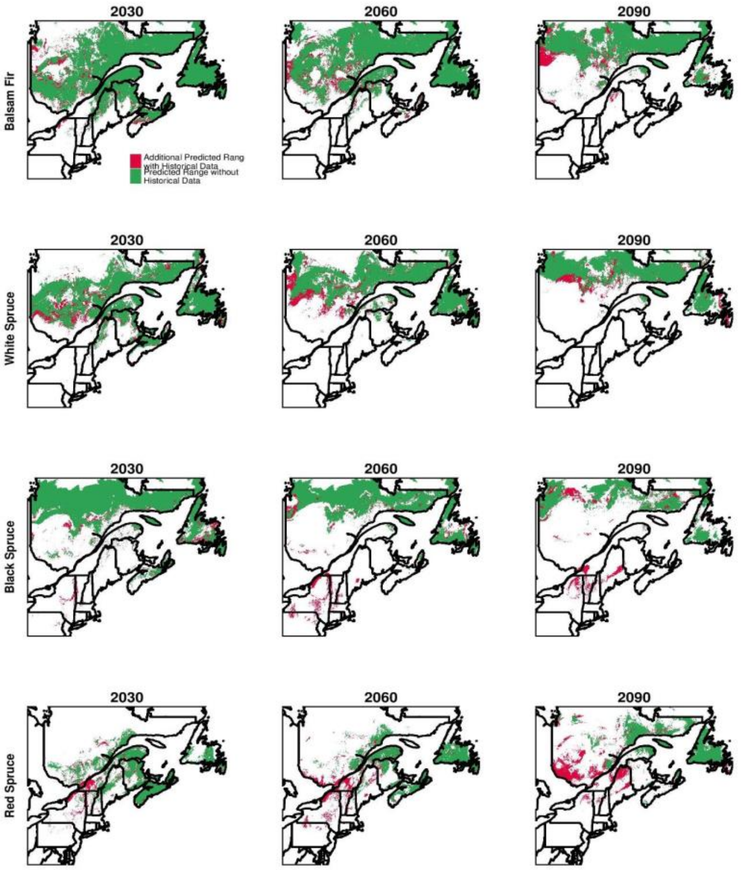


Fig 8. Predicted occurrence (>50% likelihood), with and without historical data, for (a) balsam fir, (b) white spruce, (c) black spruce, and (d) red spruce in 2030, 2060, 2090 under the ENSEMBLE RCP6 climate scenario. Additional suitable areas predicted with the inclusion of historical data are shown in red. Adapted from Andrews (2015).

Results - Tree species sensitivity

- Forest landscape projections using LANDIS-II indicated that although regional climate suitability is likely to decline, without a significant increase in the “natural” mortality of mature trees due to, for example, thermal stress or spruce budworm defoliation, spruce-fir forest will continue to be present in northern Maine ca. 2060 (Fig 9).

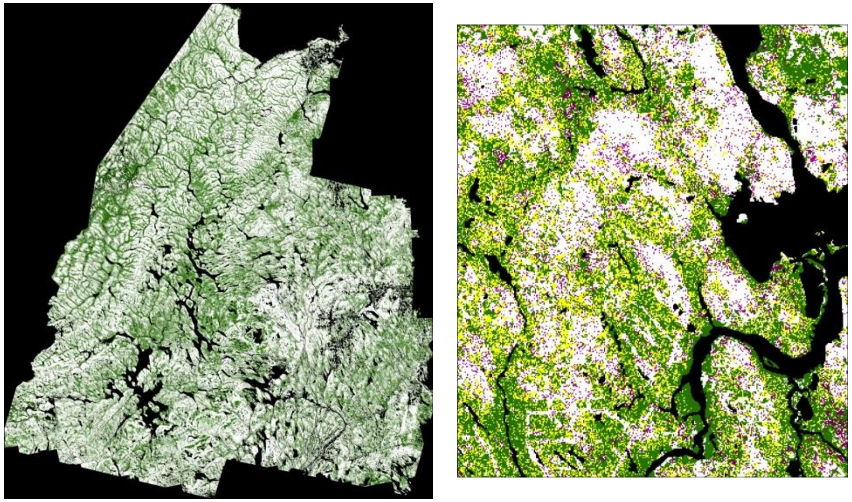


Fig 9. (a) Map of spruce-fir forest distribution (green) ca. 2060 and (b) example of the local spatial dynamics underlying the distribution. Green cells are areas that are projected to remain spruce-fir forest between 2010 and 2060, yellow are cells that convert to spruce-fir between 2010 and 2060, and red are cells that convert from spruce-fir to a different forest type between 2010 and 2060.

- Differences in model outcomes (e.g., Fig 8 vs. 9) reflect the different modeling strategies (i.e., climate envelope vs. forest landscape model), and highlight the importance of the lag in the forest system response to climate change generated by the persistence of the many trees that are currently present and still likely to be alive in 40+ years.

Results - Tree species sensitivity

- Although present, landscape projections suggest that the dominance of spruce-fir forest will decline in northern Maine as a result of post-harvest regeneration dynamics and climate change both favoring hardwood regeneration.
- In the absence of timber harvesting, climate change would have little cumulative effect on spruce-fir forest in the study area by 2060 (i.e., Succession vs. Succession X CC scenario; Fig 10).
- Interactions between climate change and harvesting (Harvest X CC), however, result in the projected reduction of percent spruce-fir forest from 27% to 18% of the forestland.

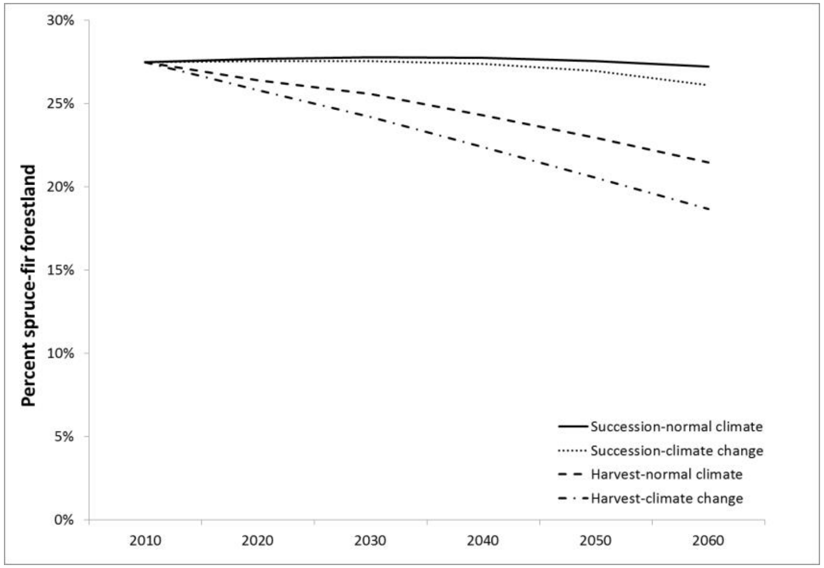


Fig 10. Change in percent of forestland classified as spruce-fir (based on live aboveground biomass) under succession-only and timber harvest scenarios (with and without climate change [HADGE RCP2.6]). Each line represents 5 runs per scenario; variability in percent spruce-fir forestland was very limited between runs (i.e., Coefficient of Variation <0.01).

- Forest conversion is predominantly from spruce-fir to mixed forest as a result of hardwood encroachment into spruce-fir forest.

Results - Tree species sensitivity

- Preliminary results suggest that with each additional landscape disturbance agent, there are new opportunities for site-level species turnover that tend to favor growth of hardwoods in areas currently dominated by balsam fir and spruce *sp.* (Fig 11).

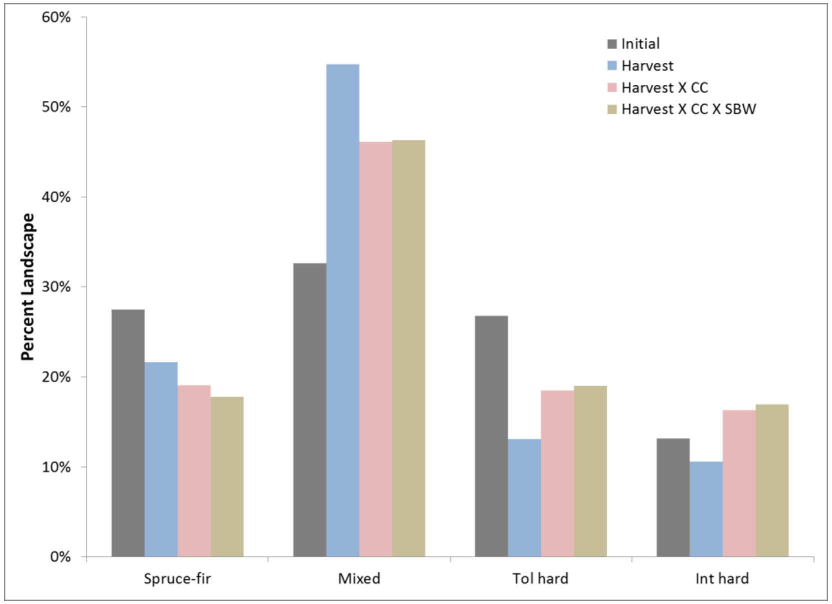


Fig 11. Percent of the landscape classified by forest type in the initial landscape (gray bar) and ca. 2060 under 3 harvest scenarios: harvest only (blue bar); harvest and climate change [HADGE RCP2.6] (red bar); and harvest, climate change and spruce budworm (green bar). Each bar represents 5 runs per scenario; variability in percent landscape by forest type was very limited between runs (i.e., Coefficient of Variation <0.02).

- In addition to harvesting and climate change, the next outbreak of spruce budworm (assumed to begin in the next 1-5 years and last ~10 years) is likely to have an additive effect on the conversion of spruce-fir forest to hardwood-dominated forest by 2060 (Fig 11).

Outreach

- Invited presentation of project results and discussion regarding implications for terrestrial wildlife at the *Climate Change Impacts on Maine's Wabanaki People* Workshop (December 13, 2016).

- Invited presentation of project results and discussion of future research directions at the *Visionary Workshop for Understanding and Forecasting the Impact of Climate Change on Maine's Forest* (October 31-November 3, 2016).

Implications for the Northern Forest region

- Results from this study indicate that predictions based on coarse-scale climate envelope models may overstress the effects of climate change on spruce-fir forest in the Northeast over the next 100 years.
- Once finer-scale variation in environmental conditions or legacy effects are taken into account a different picture emerges, suggesting that ecosystem resilience will slow the loss of spruce-fir forest in the Northeast.
- Further, timber harvesting had a larger effect on future forest composition than climate change (assuming HADGE RCP 2.6) - generally shifting competitive advantage towards hardwoods in disturbed areas.
- Climate change gave additional advantage to hardwoods in landscape projections via higher rates of establishment and annual productivity.

Future directions

- Given the importance of timber harvesting as a factor driving changing forest composition in this project, the next step in our research is to evaluate how a shift in harvesting towards salvage in response to the next outbreak of spruce budworm is likely to influence spruce-fir forest, carbon sequestration, and ecosystem stability.
- In collaboration with the Maine Forest Service, we have developed a network of budworm monitoring stations in Maine to track the emergence of the next budworm outbreak. We will be expanding site-level monitoring with additional sensors to measure ecosystem response (e.g., predator abundance) to the outbreak.
- We are currently developing a web-based mapping system to support and improve forest management planning for the next budworm outbreak.

Products

Publications

- Simons-Legaard, E., K. Legaard, A. Weiskittel. 2015. Predicting aboveground biomass with the LANDIS-II forest landscape model: A global and temporal analysis of parameter sensitivity. *Ecological Modelling* 313: 325-332.
- Andrews, Caitlin. 2015. Modeling and Forecasting the influence of current and future climate on eastern North American spruce-fir (Picea-Abies) forests. M.S. Thesis, University of Maine, Orono, Maine.

Presentations

- Simons-Legaard, E., K. Legaard & A. Weiskittel. Predicting forest aboveground biomass in diverse landscapes: A global sensitivity analysis of the LANDIS-II model. 9th International Association of Landscape Ecology World Congress, Portland, Oregon. July 8, 2015.
- Simons-Legaard, E., K. Legaard, A. Weiskittel, C. Andrews & T. D'Amato. Future distributions and productivity of spruce-fir under climate change in Maine. Maine Sustainability & Water Conference, Augusta, Maine. March 31, 2015.
- Simons-Legaard, E. & K. Legaard. Spruce budworm risk and Maine's changing landscape. Cooperative Forestry Research Unit's 2014 Spruce budworm workshop, Orono, Maine. October 30, 2014.

Grants resulting in part from the success of this project:

- Agricultural Research Station, 2016-2017: The Maine Forest Ecosystem Status and Trends (ForEST) App: An interactive mapping application to support planning for spruce budworm impact to wood supply ($96.147). PI E. Simons-Legaard.
- University of Maine Research Reinvestment Fund, 2016-2017: The Maine Forest Ecosystem Status and Trends (ForEST) App: Informing management of dynamic landscapes ($75,748). PI E. Simons-Legaard.
- University of Maine Cooperative Forestry Research Unit, 2015-2017: Identifying relationships between spruce budworm larval density, moth abundance, and forest conditions at the onset of an outbreak ($71,735). PI E. Simons-Legaard.
- US Department of Interior Northeast Climate Science Center, 2013-2015. Modeling effects of climate change on spruce-fir forest ecosystems and associated bird populations ($208,000). PI A.W. D'Amato.