Understanding landscape level factors influencing spruce budworm (SBW) outbreak patterns in Maine and forecasting future risk

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A model was developed to evaluate and predict spatial and temporal dynamics of a spruce budworm (SBW) outbreak across the complex forested landscape of Maine, USA using historical defoliation data covering approximately 50,000 km^2 and 10 years of the last SBW outbreak during the 1970s -1980s in the region. The influential factors of spatial and temporal dynamics of an SBW outbreak were identified. In addition, we evaluated the quality of several historical SBW defoliation data sets and tried to improve them using remote sensing data prior to use as input in the above mentioned model.

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Project Summary

- Spruce budworm (SBW; *Choristoneura fumiferana* (Clem.)) is the most damaging forest pest in Northeastern forests. As cyclic outbreaks occur on a regional scale, they modify carbon fluxes, as well as the vitality of the forest products industry and regional economics. The last outbreak in the 1970s in Northeastern forests affected 57 million ha of forests. However, currently there lacks a generalized modeling framework that simultaneously accounts for both the highly varied spatial and temporal dynamics of SBW outbreaks as long-lasting debates on SBW population dynamics across the landscape continue. In this study:
- First, practical methods were evaluated to add accuracy to historical defoliation data such as field data and aerial sketch maps (the current version is too coarse and inaccurate) and to be able to use the data to identify landscape factors affecting SBW outbreak patterns and develop a model to predict SBW defoliation. Several data sets including annual egg mass, SBW aerial sketch maps (ASMs), defoliation field data, historical forest cover type and Landsat-MSS imagery were collected and their accuracy was evaluated. Landsat-MSS imagery has shown to have the potential to map SBW defoliation extent at finer resolution with more accuracy than ASMs. Detection of historical SBW defoliation was possible using Landsat-MSS NDVI data and the produced maps can be used to complement coarse-resolution aerial sketch maps of the past outbreak. The shortcomings are: the unavailability of the imagery in the SBW biological window where annual defoliation can be detected and detecting light defoliation.
- Second, a highly flexible, parametric spatio-temproal model to explicitly predict SBW defoliation in continuous space and time was developed to evaluate the dynamics of SBW outbreaks across a complex forested landscape based on historical defoliation data covering approximately 50,000 km^2 and 10 years of the last SBW outbreak during the 1970s -1980s in Maine, USA, along with observations of various environmental factors. Simulations based on our model show that defoliation generally becomes ubiquitous in three years despite varying environmental and stand conditions over large ranges. Our model also indicates that current-year defoliation has almost no relationship with defoliation more than one year ago at the same location, which implies that SBW dispersal likely plays a significant role in sustaining highly dynamic defoliation across space and time. Consequently, mitigation practices like insecticide spraying may be more efficient if applied early to initial spots (epicenters) of defoliation, while management probably should focus on improving forests' resilience to withstand repeated defoliation by altering species composition. This model is readily extendable for evaluating spatial and temporal dynamics of other forms of insect defoliation across forest landscapes.

Background and Justification

- Northeastern forests of the United States and Canada provide numerous products and services for human livelihood, wildlife, and the environment, including timber, fiber products, firewood, wildlife habitat, watershed protection, carbon storage, and recreation.
- These forests have been subjected to several biotic and abiotic stressors. Biotic stressors like the outbreak of pests and pathogens—in particular, spruce budworm (*Choristoneura fumiferana* Clem.; SBW)—have greatly changed forest structure and composition in recent years. SBW is the most damaging forest pest in these regions. As outbreaks occur on a regional scale, they modify carbon fluxes, as well as the vitality of the forest products industry and regional economics. The last outbreak in the 1970s in Northeastern forests affected 57 million ha of forests.
- The current SBW outbreak started in 2006 in Quebec in Canada and by the summer of 2020 had defoliated over 13 million ha of the province. Currently, the outbreak is expected to affect Maine in the near future, with about 2.3 million ha of spruce–fir stands being at risk of SBW defoliation.

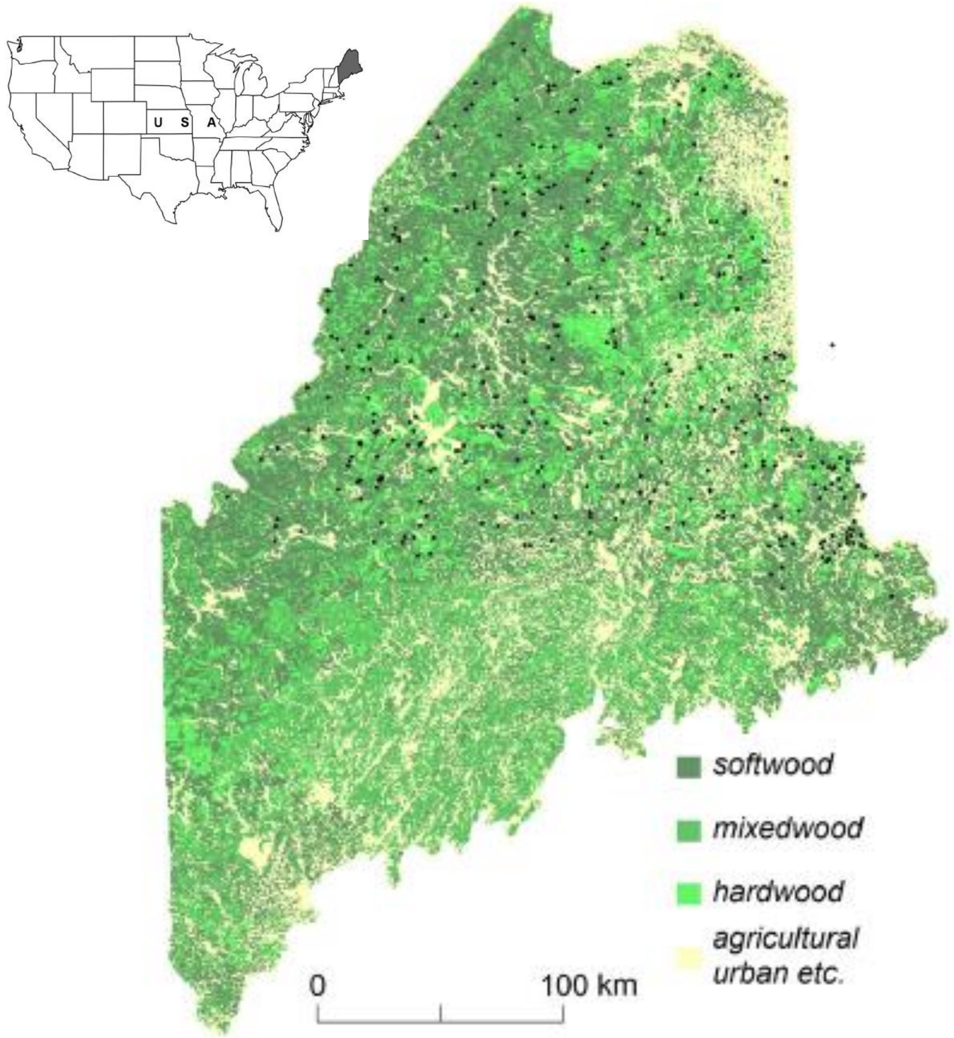

Figure 1: The extent of the study area (black dots are sample plots)

Background and Justification

- Significant efforts have been placed on modeling the dynamics of SBW defoliation, predominantly based on evaluations and syntheses of the many processes, e.g., dispersal, predation, SBW-host relationship and underlining SBW population dynamics (Royama 1984; Sturtevant et al. 2015). However there currently is no generally accepted theory or generalized modeling framework summarizing SBW population dynamics across the landscape (Pureswaran et al. 2016).
- Despite the consideration of temporal dynamics, what generally is lacking in the assessment of the dynamics of SBW outbreaks is the spatial component. The existing spatial models have shortcomings such as simultaneously evaluating and validating the varied influences of both stand characteristics and environmental factors. Given these current knowledge gaps and availability of long-term historical data, the goal of this study was to develop a parametric statistical model flexible enough to explicitly evaluate the complex spatial and temporal dynamics of SBW outbreaks.

Methods

Component 1: Evaluating historical defoliation data

- The study area: (~100*150 km^2) is located in the northern part of Maine. This region is part of New England Acadian forests that are a transition zone between boreal spruce-fir forests to the north and deciduous forests to the south.
- Several historical data sets including annual SBW egg mass, aerial sketch maps (ASMs) and defoliation field data were collected and their accuracies were evaluated. The historical ASMs of Maine were very coarse in spatial resolution, and thus were not suitable as a measure of defoliation data. Therefore expected defoliation levels derived from SBW egg-mass data were used instead for comparison with Landsat-MSS derived defoliation maps. Egg-mass data were converted to defoliation levels, using the method outlined in Simmons (1974).
- Relative radiometric normalized Landsat-MSS imagery for a pre-defoliation years (1972 and 1973), defoliated years (1975-1982) and a Landsat-derived forest cover type map for 1975 having 60m spatial resolution were acquired. The change detection method was also based on multi-date change detection using spectral vegetation indices (Rahimzadeh-Bajgiran et al., 2018). As Landsat-MSS sensors only had four spectral bands (green, red, and two NIR) with a spatial resolution of 60 m so that many common vegetation indices could not be estimated, therefore change detection was based only on NDVI (Normalized Difference Vegetation Index).

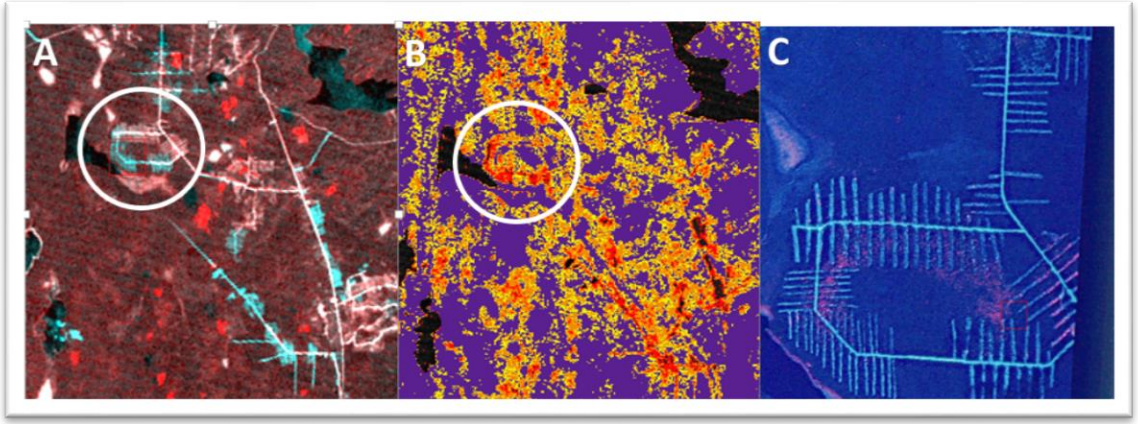

Figure 2: A) Landsat-MSS 60m RGB Delta-TCB/TCG image of 1973 to detect only forest disturbances due to harvest. White and cyan colors are harvest activities, Black and clear red spots are water bodies and clouds respectively, background reddish colors are areas with no change or change related to other disturbance b) Landsat-MSS 60m Delta-NDVI image of 1973, showing all disturbances regardless of their type in yellow, orange and red (light to severe) and purple are the areas with no change c) NASA-U2 aerial image for 1973 having 5m spatial resolution used as ground truth data. Tasseled Cap Brightness (TCB); Tasseled Cap Greenness (TCG).

Methods

Component 2: Assessing spatial and temporal dynamics of a spruce budworm outbreak

- Study area: The vast spruce-fir forests in the state of Maine, USA, which are primarily distributed across the northern parts of the state. Specifically, the extent of our defoliation data is 44.94°–47.30° N and 67.30°–70.73° W, which covers an area of approximately 50,000 km^2.
- Data:
  i. The Growth Impact Study data collected between 1975 and 1985 including 376 0.02-ha plots spread across the spruce-fir forests of Maine (Solomon and Brann 1992). These data contain annual individual tree measurements and SBW defoliation data.
  ii. The daily temperature and monthly wind data (Global Historical Climate Network data available from the US National Centers for Environmental Information). 62 stations located in the state of Maine were used in this study during the years of 1975 to 1984.
  iii. Historical Landcover data: The National Water-Quality Assessment Project refined the US Geological Survey historical land use and land cover data derived from aerial photographs from the 1970s having 96 m spatial resolution.
  iv. Digital elevation model data (Maine office of GIS).

Table 1 A summary of the forest and environmental attributes in this study

Attributes	Mean	SD	Min	Max
Volume (m^3 ha^{-1})	225	112	2	626
Stand density index	583	237	16	1395
Relative stand density	0.30	0.12	0.01	0.66
Dominant height (m)	19.2	2.9	6.7	28.0
Cumulative defoliation (%)	85	86	0	586
% balsam fir in volume	26	24	0	100
% white spruce in volume	3	11	0	100
% black spruce in volume	3	13	0	100
% red spruce in volume	25	27	0	100
% hardwood in volume	19	21	0	100
Wind direction (degree)[1]	262	77	135	360
Wind velocity (m s^{-1})[1]	11.9	2.4	8.5	15.6
Habitat suitability	0.60	0.13	0.00	1.00
Climate site index[2]	13.5	1.4	9.2	19.0
Wetness index	7.3	2.9	0.8	15.8
Slope (%)	9.8	14.0	0.0	132.7
Aspect (degree)	174	113	0	360
Elevation (m)	263	130	41	691

[1] Based on fastest mile wind direction and velocity

[2] Introduced by Weiskittel et al. (2011)

Method

- Method: Spatial and temporal dynamics of an SBW outbreak across the landscape were based on predictions of percentage defoliation at every specific location and time. These predictions were attributed to local factors at the stand scale (i.e., intrinsic stand characteristics, e.g., species composition, to support local SBW population) and landscape factors (e.g., landscape structure and weather conditions affecting the dispersal of SBW). The model shares similarities with the one proposed by Meyer et al. (2012) however our model is notably different in that percentage defoliation is explicitly used as the response variable and also is more flexible for using geo-spatial data at different resolutions. Simulations of spatial and temporal dynamics of an SBW outbreak were performed at a resolution of 10 km across a demonstrative area of 160 km (longitudinal) × 240 km (latitudinal). These simulations were based on the above model and scenarios defined in Table 2.

Table 2 Scenarios in simulations of spatial and temporal dynamics of SBW outbreaks, where *D* is stand relative density, *C* is host tree percentage, W_v is the velocity of wind, W_d is the direction of wind, *H* is dominant height, *L* is the metric of landscape connectivity, *Def* is defoliation, and *ΔE* is the difference in elevation

Predictor	Scenario								
	Reference	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*
D	0.31 (1975 mean)	As reference						0.20	0.40
C	59% (1975 mean)					50%	75%		
W_v	11.2 m s^{-1} (1975 mean)			5.0 m s^{-1}	15.0 m s^{-1}				
W_d	225° (1975 value)	270°	315°						
H	19.0 m (1975 mean)					As reference			
L	0.60 (1975 mean)								
Def	preset initial values								
ΔE	as is								

Results (Component 1):

Table 3 Results of regression analysis between egg-mass-derived expected defoliation levels and Landsat-MSS-derived NDVI and defoliation occurrence analysis (Tot.: Total; Ave.: Average).

Year	Egg Mass Counts Class/100 ft^2	Expected Defoliation Class (%)	Samples per Egg-Mass Class	% of Total Egg-Mass Samples	% Correctly Identified	*p*-Value	Pseudo R^2 (Nagelkerke)
1975	0	0	3	1	67	0.001	0.038
	1–50	1–12	29	8	41		
	51–170	13–42	87	25	45		
	171–320	43–78	87	25	68		
	321–+400	79–100	143	41	60		
	-	-	Tot. 349	Tot. 100	Ave. 57		
1982	1–50	1–12	52	21	42	0.002	0.041
	51–170	13–42	55	22	36		
	171–320	43–78	48	20	56		
	321–400	79–98	92	37	53		
	-	-	Tot. 247	Tot. 100	Ave. 47		

- ✓ The relationship between defoliation levels estimated from egg mass data and change in mean NDVI values was weak, but statistically significant.
- ✓ Due to the weak statistical relationship between the expected defoliation data and NDVI in Maine, but better accuracy for defoliation identification (%correctly identified data), only defoliated versus non-defoliated classes were mapped.
- ✓ It is evident that Landsat-MSS and expected defoliation data present more details about the status of defoliation over coniferous forests than ASMs.
- ✓ Apparently, forest composition data were not incorporated into the ASM defoliation estimates.

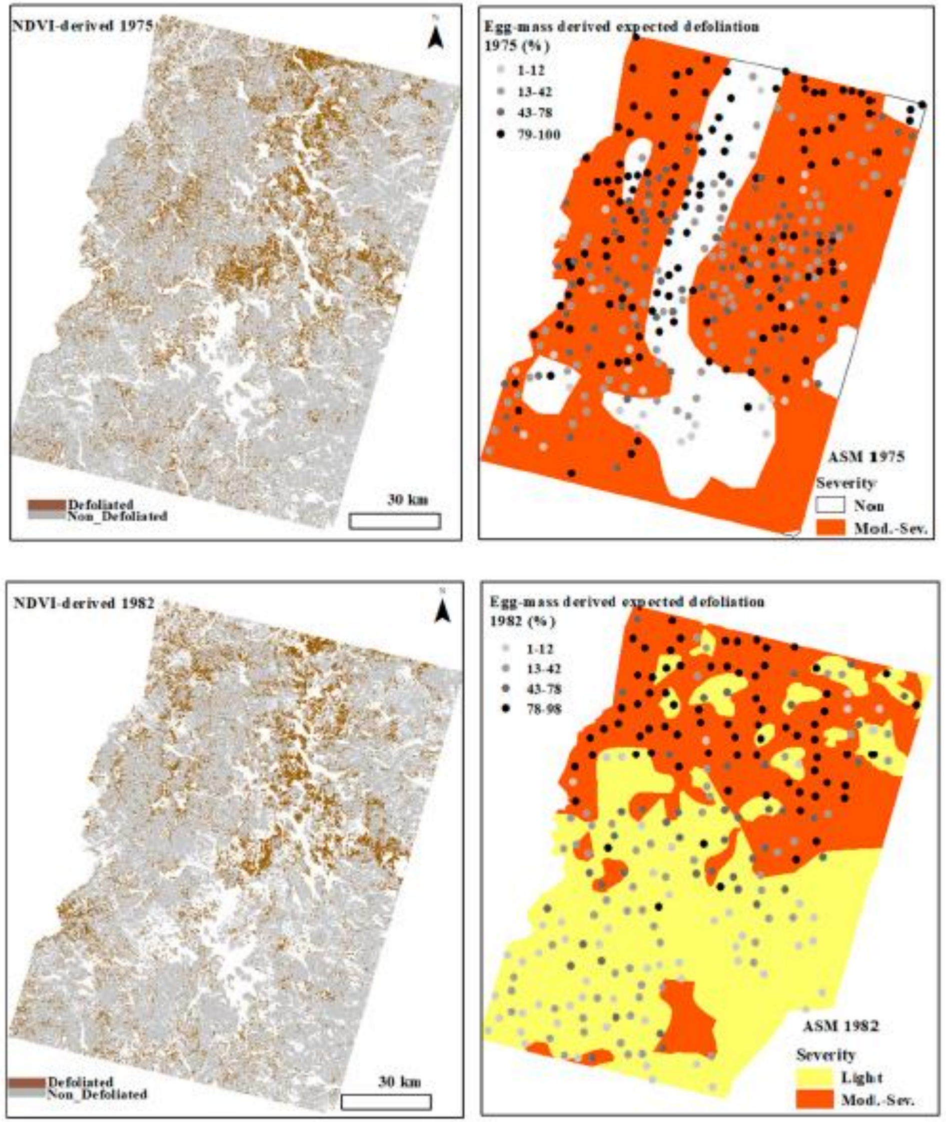

Figure 3: Top: Landsat-MSS SBW defoliation occurrence map for 1975 at 60 m spatial resolution, and expected defoliation (%) derived from egg-mass counts in 1975 overlaid on an ASM SBW defoliation map for 1975. Bottom: Landsat-MSS SBW defoliation occurrence map for 1982 at 60 m spatial resolution, and expected defoliation (%) derived from egg mass counts in 1982 overlaid on an ASM SBW defoliation map for 1982.

Results (Component 2):

Influential factors of spatial and temporal dynamics of an SBW outbreak (Table 4):

- The most influential factor in SBW defoliation dynamics across the landscape is defoliation itself (at a given forest location and its neighbors). It has a 31.7 times influence compared to the least influential factor of stand relative density (as a reference, i.e., its influence was scaled to be one) when the mean distance between forest locations is 40 km.
- Landscape connectivity is the second most influential factor while host tree percentage is the most influential endemic factor (intrinsic stand characteristic) of those affecting SBW outbreak dynamics evaluated in this study.
- Increases in landscape connectivity and stand relative density, as well as decreases in elevation from source to destination locations of defoliation reduce the level of defoliation at the destination location.
- Increases in defoliation (at a forest location itself and neighboring locations), host tree percentage, wind, stand dominant height, and differences in elevation are all positively related to subsequent intensification of an SBW outbreak.

Table 4 Parameter estimates, standard errors, and p-values for the predictors in our model

Predictor	Symbol	Unit	Parameter estimate	Standard error	p-value
interaction between relative density and dominant height	$D \cdot H$	0-1 ratio · m	-1.383	0.118	<0.01
dominant height	H	m	0.583	0.047	<0.01
interaction between relative density and host tree percentage	$D \cdot C$	0-1 ratio · %	41.73	2.575	<0.01
Defoliation	Def	%	0.093	0.003	<0.01
landscape connectivity	L	0-1 ratio	-18.59	4.356	<0.01
wind	W	$m\ s^{-1}$	1.127	0.479	0.02
interaction between wind and elevation difference	$W \cdot \Delta E$	$m\ s^{-1} \cdot m$	0.016	0.011	0.12

Results (Component 2):

Simulations of spatial and temporal dynamics of an SBW outbreak:

- ✓ Host tree percentage and velocity of wind have noticeably greater effects than the other factors on the spread and intensification of SBW defoliation across the landscape in simulated outbreaks
- ✓ SBW defoliation spreads over long distances (100+ km in cases) and results in relatively distinctive spatial patterns of defoliation in the first two years of simulated outbreaks in various scenarios. However, defoliation generally becomes ubiquitous in three years despite it is initiated in at only four locations in all scenarios (Figure 4).

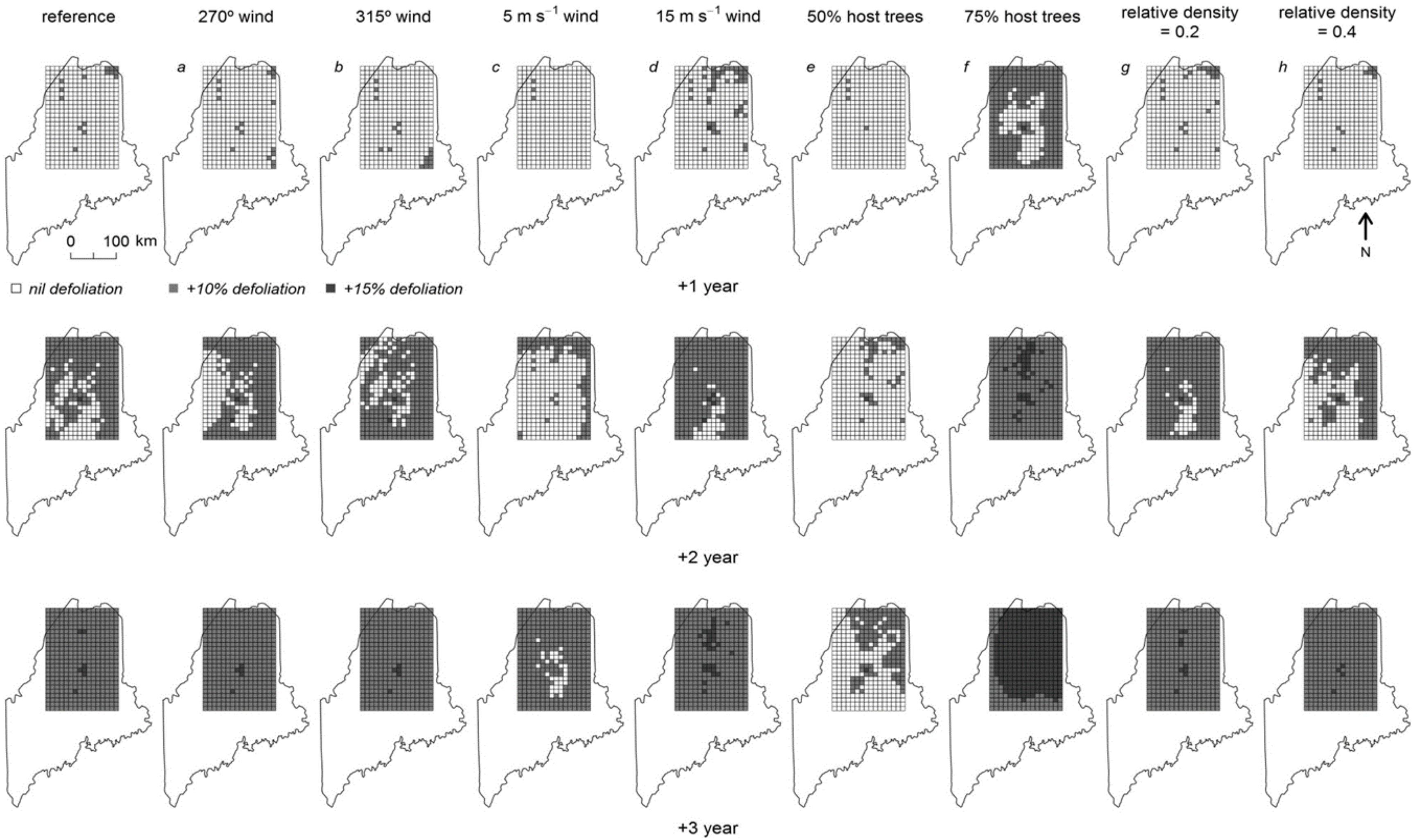

Figure 4: Simulated spatial and temporal dynamics of an SBW outbreak under various scenarios introduced in Table 4

Implications and applications in the Northern Forest region and future directions

- The immediate application of the results of this research is for the northern forest region as explain earlier in this report.
- The quantitative information generated by our model is both flexible in spatial and temporal scales and directly usable in existing forest growth and yield modeling frameworks and management decision support systems, which are useful tools for assessing health, productivity, and succession of forests influenced by SBW defoliation.
- Our analysis is readily extendable to evaluating spatial and temporal dynamics of other forms of defoliation across forest landscapes given the general robustness, flexibility, and strong performance of the approach.

Meyer, S., Elias, J. and Höhle, M., 2012. A space–time conditional intensity model for invasive meningococcal disease occurrence. *Biometrics*, *68*(2), pp.607-616.

Pureswaran, D.S., Johns, R., Heard, S.B. and Quiring, D., 2016. Paradigms in eastern spruce budworm (Lepidoptera: Tortricidae) population ecology: a century of debate. *Environmental Entomology*, *45*(6), pp.1333-1342.

Rahimzadeh-Bajgiran, P., Weiskittel, A., Kneeshaw, D. and MacLean, D., 2018. Detection of annual spruce budworm defoliation and severity classification using Landsat imagery. *Forests*, 9(6), p.357.

Royama, T.O., 1984. Population dynamics of the spruce budworm Choristoneura fumiferana. *Ecological Monographs*, *54*(4), pp.429-462.

Simmons, G.A., 1974, November. Influence of spruce budworm moth dispersal on suppression decisions. In *Proceedings of a symposium on the spruce budworm. USDA, Forest Service. Miscellaneous Publication* (No. 1327, pp. 170-177).

Solomon, D.S. and Brann, T.B., 1992. *Ten-year impact of spruce budworm on spruce-fir forests of Maine. US Dept. of Agriculture, Forest Service, Northeastern Forest Experiment Station*. General Technical Report NE-165. Radnor, PA.

Sturtevant, B.R., Cooke, B.J., Kneeshaw, D.D. and MacLean, D.A., 2015. Modeling insect disturbance across forested landscapes: insights from the spruce budworm. In *Simulation modeling of forest landscape disturbances* (pp. 93-134). Springer, Cham.

Products

Refereed Journal Publications (USDA Forest Service-NSRC was acknowledged in both publications below)

1. Chen, C., Rahimzadeh-Bajgiran, P. and Weiskittel, A., 2021. Assessing spatial and temporal dynamics of a spruce budworm outbreak across the complex forested landscape of Maine, USA. *Annals of Forest Science*, *78*(2), pp.1-14.
2. Rahimzadeh-Bajgiran, P., Weiskittel, A.R., Kneeshaw, D. and MacLean, D.A., 2018. Detection of annual spruce budworm defoliation and severity classification using Landsat imagery. *Forests*, *9*(6), p.357.

Conference and Workshop Presentations

1. Rahimzadeh-Bajgiran, P., Weiskittel, A., Kneeshaw, D., MacLean, D.A. SBW defoliation detection using satellite remote sensing techniques: lessons from the past and future outlook, Spruce Budworm Early Intervention Strategy Science Workshop – March 13-14, 2018, Fredericton, NB, Canada.
2. Rahimzadeh-Bajgiran, P. Weiskittel, A., Kneeshaw, D., MacLean, D.A. A multi-index Landsat-derived model for spruce budworm defoliation detection and quantification: Examples of past and current outbreaks (1970s and 2000s). ASPRS-Pecora 20 Memorial Remote Sensing Symposium, Sioux Falls, SD, U.S.A, Nov.13-16, 2017.
3. Rahimzadeh-Pajgiran, P., Spruce budworm-induced forest defoliation and remote sensing opportunities, Atmospheric Transport Model working group meeting, Sept. 27th, 2017, Quebec, Canada.

Grants resulting in part from the success of this project

1. NASA EPSCoR (2019-2022): Multi-scale remote sensing approaches for forest health assessment (Lead PI: Parinaz Rahimzadeh-bajgiran)
2. Cooperative Forestry Research Unit (CFRU), Maine (2017-2019): Developing a refined forest site productivity map by linking biomass growth index (BGI) to remotely sensed variables (Lead PI: Parinaz Rahimzadeh-bajgiran)