Testing the value of high resolution LiDAR data for assessing the structure and integrity of forest canopies that influence tree health, insect populations, and bird habitats

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We found consistent reductions in xylem increment growth, decreases in foliar nutrition and crown health, and increases in stand mortality related to high understory closure as documented through LiDAR. This suggests that LiDAR measures can reflect certain aspects of forest health, especially competitive interactions, not just among overstory trees for light, but also interactions between overstory trees and understory vegetation for resources.

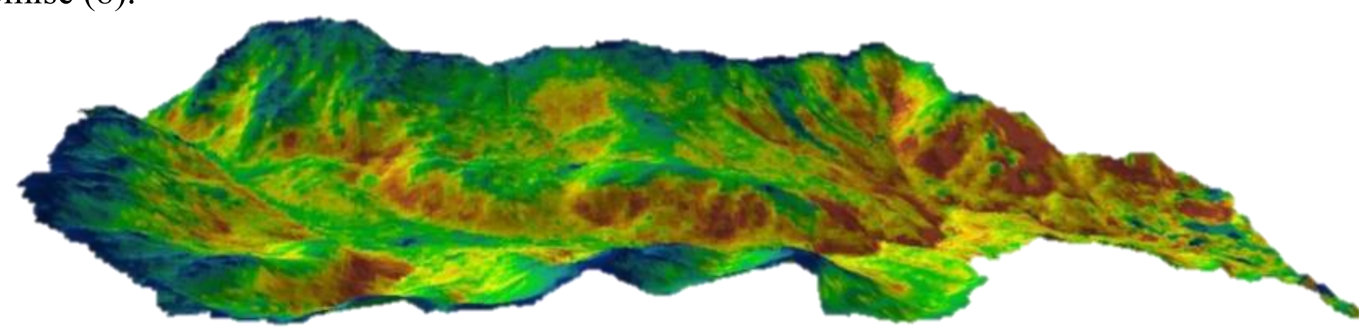
Funding support for this project was provided by the Northeastern States Research Cooperative (NSRC), a partnership of Northern Forest states (New Hampshire, Vermont, Maine, and New York), in coordination with the USDA Forest Service. http://www.nsrcforest.org

Project Summary

- Rationale: As anthropogenic disturbances increase in extent, rate, and severity, managers and biologists must develop cost-effective techniques to evaluate the fundamental habitat features that shape forest health and biodiversity. This proposal used remotely sensed Light Detection and Ranging (LiDAR) data to characterize vegetation structure.
- Methods: We assessed the relationship of LiDAR to sugar maple (*Acer saccharum* Marsh) and yellow birch (*Betula alleghaniensis* Britton) health and productivity on 36, 50m radius plots, with nine plots in each of four LiDAR structural categories: 1) high crown and high understory closure, 2) high crown and low understory closure, 3) low crown and high understory closure, and 4) low crown and low understory closure. Ground-based measures of canopy structure, site, stand and individual tree measures were collected on all plots during summer 2012.
- Major findings/outcomes: We found significant differences among LiDAR categories for numerous tree measures. Reductions in basal area increment growth for sugar maple trees, decreases in foliar nutrition for yellow birch, and reductions in overall crown health were all associated with high understory and overstory closure.
- Implications for the Northern Forest region: This suggests that LiDAR measures can detect competitive interactions between overstory trees and understory vegetation, and that LiDAR shows promise for identifying stands in poor health due to competition and overstocking.

Background and Justification

Ecological studies have suggested that the spatial distributions of fundamental ecological parameters, including variations in vegetation structure and composition, are central in explaining patterns of biodiversity (1, 2). In particular, forest canopies are important sources of nutrient and water uptake, and are drivers of net primary production that support and influence higher trophic levels. Quantifying the vertical structure and complexity of forest canopies has traditionally been limited in spatial extent, as well as limited to expensive and labor-intensive field based data collection (3, 4). Passive remote sensing techniques that are useful for assessing canopy structure and complexity at larger spatial scales have been limited by their two-dimensional nature (3, 5, 4). Due to these limitations, and especially at larger spatial scales, canopy structure and complexity have not been fully analyzed and integrated as modulators of biodiversity. Recent advances in LiDAR have provided a new source of geospatial data that provides detailed information of the 3-D structure of forest canopies (4). Coarse-scale LiDAR has already been used to estimate the vertical distribution and complexity of canopies in deciduous hardwood forests and relate these to one important indicator of biodiversity: bird species richness (6, 7). However, improvements in habitat analysis and prediction afforded by the use of high-resolution LiDAR data have not been fully evaluated. In addition, the use of LiDAR data to remotely assess crown features that relate more directly to forest health and productivity (e.g., crown density, vigor and dieback) is uncommon but shows promise (8).



LiDAR image of the Hubbard Brook Experimental Forest (9)

Background and Justification
Literature Cited

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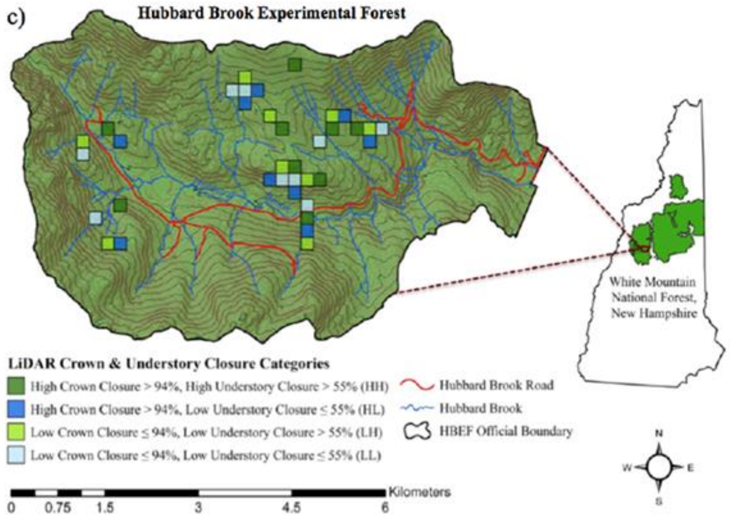
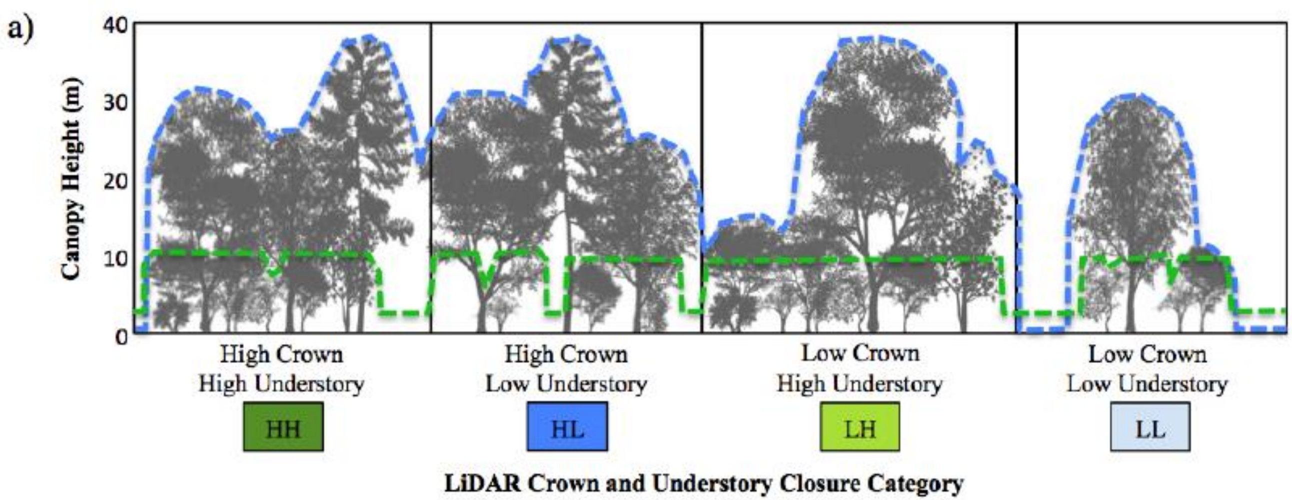
Methods: Study site and experimental design



Study site: Hubbard Brook Experimental Forest, West Thornton, NH

We assessed the relationship of LiDAR to sugar maple (*Acer saccharum* Marsh) and yellow birch (*Betula alleghaniensis* Britton) health and productivity on 36, 50m radius plots, with nine plots in each of four LiDAR structural categories: 1) high crown and high understory closure, 2) high crown and low understory closure, 3) low crown and high understory closure, and 4) low crown and low understory closure. Ground-based measures of canopy structure, site, stand and individual tree measures were collected on all plots during summer 2012.



Methods: Field Measurements

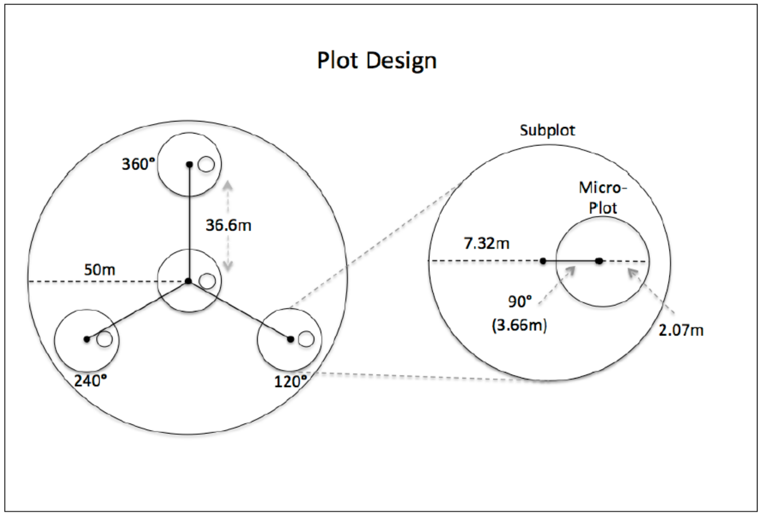


Figure 2. Diagram of the basic plot design, which was based on FIA protocols (Bechtold 2005).

Plot: Two xylem increment cores collected for each of five selected dominant and co-dominant sugar maple and yellow birch trees to determine tree age and assess annual growth. Foliar nutrition was assessed by collecting sunlit/upper canopy foliage using shotguns to obtain samples in early August from the same trees. Cation concentrations – calcium (Ca), aluminum (Al), potassium (K), phosphorous (P), manganese (Mn), and magnesium (Mg) – were measured from the digested foliage using inductively coupled plasma atomic emission spectrometry.

Subplot: Inventories following USDA Forest Inventory & Analysis (FIA)protocols were conducted on trees > 12.5 cm, including species, dbh, crown status, and canopy health.

Micro-plot: Inventory of all trees 2.5 to 12.5 cm DBH using the same measures as collected for subplots.

Methods: Field Measurements

Arthropod Abundance and Diversity

- Branch Clippings - Max Height of 10 meters
- Two Trees Per Species (Yellow Birch & Sugar Maple) Per Plot
- Arthropods Counted, measured, and Identified to Order

Bird Abundance and Diversity

- 50m – Fixed Radius Point Counts
- Ten Minute Surveys – Three 3-Min 20-Sec Intervals
- Two Observers Visited Each Plot Twice

Results: Dieback and standing dead

Table 1. Mean (± SE) sub-plot standing dead basal area, plot level crown vigor index and percent branch dieback by LiDAR category, collected during 2012 at the Hubbard Brook Experimental Forest, NH, USA.

		LiDAR crown & understory closure category			
Response variable	Significance	High crown High understory (HH)	High crown Low understory (HL)	Low crown High understory (LH)	Low crown Low understory (LL)
<u>Decline</u>					
% branch dieback	**	**31.60 ± 2.27a**	**23.86 ± 1.48b**	**30.52 ± 3.03ab**	**31.17 ± 2.12a**
Crown vigor index	*	2.34 ± 0.09	1.97 ± 0.07	2.27 ± 0.16	2.22 ± 0.10
<u>Basal area</u> (m^2/ha)					
Standing dead	*	6.26 ± 1.30	2.46 ± 0.50	5.13 ± 1.03	4.86 ± 1.15

** and in bold $P \leq 0.05$, * $P \leq 0.10$

Means (± SE) with differing letters are statistically significantly different based on a Tukey HSD test

Percent branch dieback was significantly different (P ≤ 0.05) among LiDAR categories, with HH and LL closure categories exhibiting significantly greater dieback than the HL category (Table 1). Crown vigor index was only marginally different among LiDAR categories (P ≤ 0.10), with a trend for LiDAR categories with high understory closure having a higher crown vigor index (meaning poorer condition) regardless of crown closure (Table 1). Standing-dead basal area was also only marginally different (P ≤ 0.10) among the LiDAR categories, with a tendency for plots with HL closure to exhibit the least standing-dead basal area (Table 1).

Results: Basal area increment

Table 2. Mean (± SE) basal area increment (cm^2) for sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) by LiDAR category, collected during 2012 at the Hubbard Brook Experimental Forest, NH, USA.

Response variable	Significance	LiDAR crown & understory closure category: High crown High understory (HH)	High crown Low understory (HL)	Low crown High understory (LH)	Low crown Low understory (LL)
Basal area increment (cm^2)					
Sugar Maple:					
2000-2012	**	**7.05 ± 1.58**^{b}	**11.09 ± 0.96**^{a}	**10.92 ± 1.58**^{ab}	**10.33 ± 1.99**^{ab}
2009 (year of LiDAR acquisition)	**	**7.73 ± 1.74**^{b}	**11.69 ± 0.98**^{ab}	**11.41 ± 1.42**^{ab}	**12.44 ± 2.66**^{a}
Post-ice storm/pre-LiDAR (1999-2008)	**	**7.05 ± 1.61**^{b}	**11.27 ± 1.00**^{a}	**10.99 ± 1.62**^{ab}	**10.11 ± 1.93**^{ab}
Pre-ice storm (1988-1997)	**	**7.61 ± 1.82**^{b}	**13.69 ± 1.32**^{a}	**11.77 ± 1.08**^{ab}	**11.33 ± 1.96**^{ab}
Yellow Birch:					
2000-2012	NS	10.93 ± 1.44	10.99 ± 1.42	12.01 ± 1.64	11.37 ± 0.59
2009 (year of LiDAR acquisition)	NS	15.13 ± 2.20	14.36 ± 1.38	15.56 ± 2.36	14.86 ± 0.93
Post-ice storm/pre-LiDAR (1999-2008)	NS	10.34 ± 1.34	10.63 ± 1.48	11.45 ± 1.53	10.87 ± 0.58
Pre-ice storm (1988-1997)	NS	12.22 ± 1.30	13.10 ± 2.14	12.80 ± 1.51	12.31 ± 0.99

** and in bold $P \leq 0.05$, "NS" denotes not significant

Means (± SE) with differing letters are statistically significantly different based on a Tukey HSD test

Measures of BAI were significantly different among LiDAR categories for sugar maple but not yellow birch (Table 2). Overall, sugar maple BAI was lowest for trees in the HH category. For 2009 (year of LiDAR), BAI growth for sugar maple in HH plots was significantly lower than in LL plots, with growth in HL and LH being intermediate. For the periods pre- (1988-1997) and post- (1999-2008) ice storm and for the period of most recent growth (2000-2012), growth of maples in HH plots was lower than growth on HL plots, with growth on LH and LL plots being intermediate (Table 2).

Results: Basal area increment

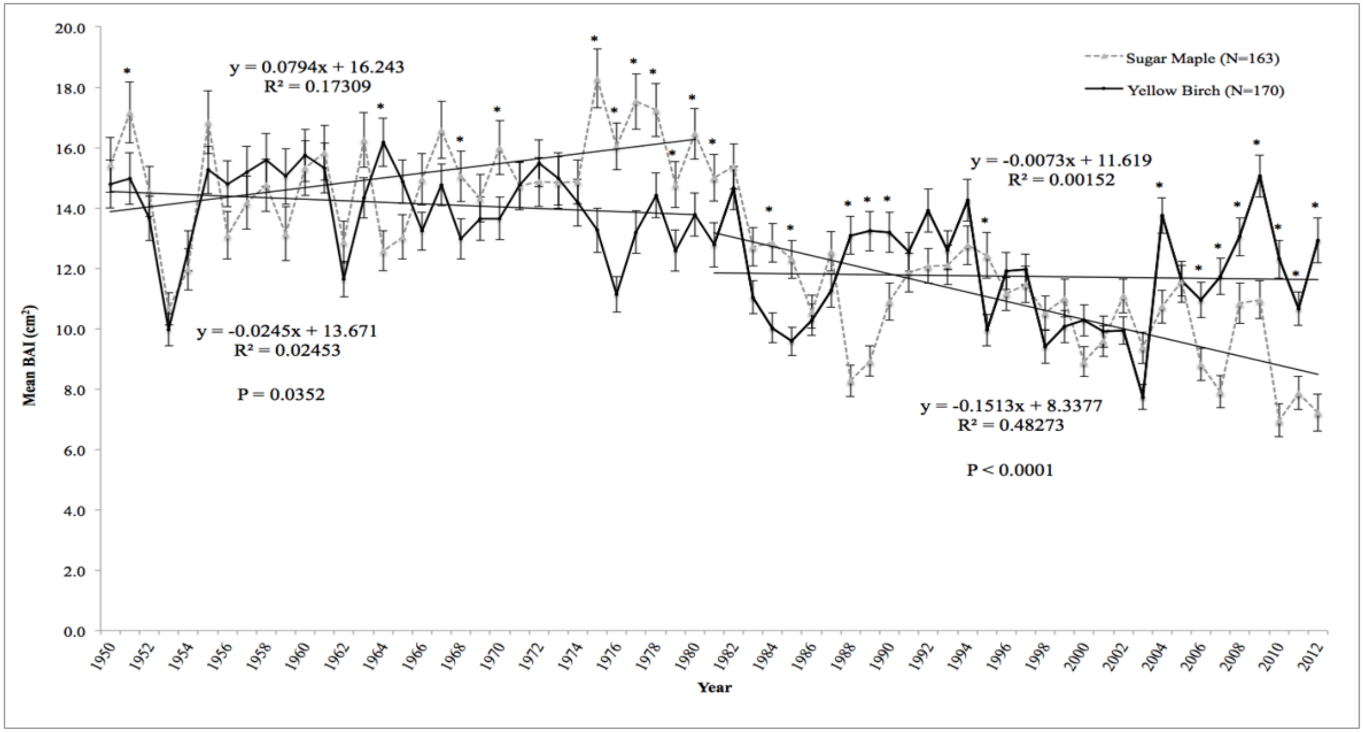


Fig. 2. Mean basal area increment (BAI; ± SE) for sugar maple and yellow birch trees from 1950 – 2012 at the Hubbard Brook Experimental Forest, NH, USA. Individual years that are significantly different between species are indicated by an asterisk (based on an orthogonal contrast between species with $P \leq 0.05$). Slope analyses indicate different linear growth trajectories for each species and its significance between species for the years 1950 – 1980 and 1981 – 2012.

Sugar maple BAI growth significantly increased from 1950 through 1980, but significantly declined thereafter (Fig. 2). In contrast, yellow birch growth was fairly constant over time, although year-to-year variation was high (Fig. 2). From 1950 through 1985, sugar maple and yellow birch had either equal growth (23 years) or sugar maple growth exceeded that of yellow birch (12 years) (Fig. 2). However, after 1985 sugar maple growth was never greater than that of yellow birch (Fig. 2).

Results: Foliar nutrients

Table 4. Mean (± SE) foliar Ca and Ca:Al nutrition (mg·kg^{-1}) for sugar maple (*Acer saccharum) and* yellow birch (*Betula alleghaniensis*) by LiDAR category, collected during 2012 at Hubbard Brook Experimental Forest, NH, USA.

Foliar nutrition (mg·kg^{-1})	Significance	LiDAR crown & understory closure category: High crown High understory (HH)	High crown Low understory (HL)	Low crown High understory (LH)	Low crown Low understory (LL)
Sugar maple:					
Ca	NS	4965. 9 ± 565.8	5534.0 ± 192.2	5650.1 ± 626.4	5214.3 ± 429.9
Mg	NS	976.8 ± 107.6	1045.7 ± 50.5	1035.3 ± 107.5	972.8 ± 89.5
Mn	NS	1307.4 ± 192.3	1020.6 ± 104.6	1324.3 ± 169.0	989.5 ± 108.7
Al	NS	69.8 ± 10.9	63.5 ± 9.1	70.8 ± 11.7	72.4 ± 10.3
Ca:Al molar ratio	NS	55.71 ± 8.91	70.41 ± 11.09	70.14 ± 18.9	55.91 ± 8.49
Yellow birch:					
Ca	*	**7966.97 ± 489.31^{b}**	**10122.90 ± 667.88^{a}**	**7969.18 ± 384.25^{b}**	**8757.82 ± 472.02^{ab}**
Mg	NS	2347.4 ± 140.4	2480.0 ± 133.0	2197.2 ± 88.1	2323.2 ± 125.3
Mn	NS	1794.3 ± 259.1	1727.2 ± 200.5	1522.9 ± 251.6	1322.6 ± 127.0
Al	NS	68.13 ± 8.3	59.0 ± 9.3	61.3 ± 9.2	51.7 ± 6.9
Ca:Al molar ratio	NS	85.06 ± 8.35	132.98 ± 16.67	101.31 ± 13.83	130.84 ± 18.4

* and in bold $P \leq 0.05$, "NS" denotes not significant

Means (± SE) with differing letters are statistically significantly different based on a Tukey HSD test

No differences in foliar cation concentrations associated with LiDAR categories were found for sugar maple (Table 4). For yellow birch only foliar Ca concentrations differed significantly; plots with HL closure exhibited significantly greater foliar Ca than HH and LH plots.

Results: Birds and arthropods

- None of the measures of avian abundance or diversity varied among the LiDAR categories. Furthermore, linear relationships between avian abundance and diversity with arthropod abundance were also not significant, regardless of LiDAR categories.
- Measures of arthropod abundance, in particular, total arthropod mass and Lepidopteran mass, were not significantly different among LiDAR categories. The lack of significant differences for arthropod abundance among LiDAR categories presented here are not surprising because measures of mid-canopy foliar N, P, and K often associated with arthropod abundance were also not significantly different among LiDAR categories.
- Linear relationships comparing mid-canopy foliar N and P to total arthropod mass and Lepidopteran larval mass were significant and positive, with N having a considerably greater effect on size than P. These findings are in agreement with previous findings on the association of N and P with arthropod abundance and performance.

Results: Summary

- Overall, HH plots exhibited significantly greater percent dieback and tended to have poorer crown vigor and greater standing dead basal area than HL plots, with the LH and LL plots being intermediate (Table 1).
- LiDAR also showed utility in differentiating annual BAI growth for sugar maple but not yellow birch. In three of the four time periods assessed, including before and after the 1998 ice storm.
- The poorer health (Table 1) and lower growth of sugar maple (Table 2) in HH compared to HL plots may indicate that, at least when overstory cover is high, added competition from understory vegetation may reduce stand vigor and sugar maple productivity.
- We propose that competition for nutrients between understory and overstory plants may be responsible for the differences in health and productivity measures we detected among LiDAR plots.
- To our knowledge, there are no published ranges for healthy foliar cation concentrations for yellow birch. However, yellow birch generally accumulated higher concentrations of cations other than Al than did sugar maple (Table 4). Similar to health and productivity measures, foliar Ca concentrations were significantly lower in HH plots than in HL plots, with concentrations in LH and LL plots tending to be intermediate (Table 4). This may indicate that in areas with high crown competition, yellow birch with less understory competition may have greater access to Ca, which can be limiting at HBEF.

Implications and applications in the Northern Forest region

Within the northern forest region there are many anthropogenic factors (e.g., acidic deposition, climate change, and non-native invasive pests) that will likely change the forest structure and composition over time. In response to this, forest and wildlife professionals need cost effective means to manage and conserve the northern forest. The results from this study illustrate the potential of using canopy and understory closure metrics derived from high-resolution LiDAR data to differentiate stands based on metrics of forest health and productivity. LiDAR has been shown to be a useful tool in assessing basic measures of forest structure, such as canopy height, basal area, leaf area index (Hudak et al. 2002, Næsset 2007, Jensen et al. 2008), as well as certain characteristics of higher trophic levels (e.g., bird species richness and bird prevalence) that are dependent upon canopy structure (Goetz et al. 2007, Swatantran et al. 2012). However, the ability of LiDAR to bridge the gaps between forest canopy structure, tree health and productivity measures had not been previously evaluated. Our results show the novel ability of LiDAR data to remotely assess differences in stand condition. These differences were primarily detected for plots with closed canopies that varied in understory closure, suggesting that increased competition from understory plants reduced overstory vigor, sugar maple BAI growth, and foliar Ca concentrations in yellow birch.

Implications and applications in the Northern Forest region

The consistency of LiDAR in defining attributes in forest canopy and understory structure reflective of tree functional traits is somewhat surprising considering two limitations inherent to the current study. First, LiDAR categories were calculated across large spatial extents (4 ha) deemed important for ecological function. LiDAR categories based on broad spatial averages could have masked 50 m plot-based patterns in tree health and productivity due to a mismatch in scale. Second, LiDAR continuous point cloud data had to be converted to categorical LiDAR classes, which undoubtedly simplified the informational content of estimated forest structure. Despite these limitations, LiDAR estimates could differentiate between a range of stand -based measures of health and productivity. The breadth and consistency of these relationships is likely testament to the strong predictive capacity of LiDAR-based measures of forest structure for elucidating associated patterns of tree and forest function. The results suggest that LiDAR has the potential to be used as a relatively low cost method to assess forest health over large spatial scales.

Future directions

- Large datasets of forest health and productivity and arthropod and bird abundance and diversity were collected for this project. Regardless of their relationship to LiDAR, they could provide valuable information about ecosystem functioning and trophic interactions within the broader northern forest, especially in the context of global climate change. Further analyses of sugar maple and yellow birch growth using the xylem increment cores and their crown vigor status have already begun.

- Previous research has shown increased yellow birch and decreased sugar maple growth at HBEF (van Doorn et al. 2011). Xylem increment cores and foliar nutrition data could help evaluate the nature and timing of recent changes in the growth of these species.

Future directions

- Scale and/or classification scheme played an important role in LiDAR’s relationship to many of the response variables. Future directions of this research include looking at different ways to summarize and test the LiDAR against ground-based metrics (e.g., looking at the density of points in the raw LiDAR point cloud as a measure of canopy vertical structure as opposed to the percent understory closure as calculated from the 0.5-10m Above Ground Level surface model).
- Future directions should also include using structural equation modeling (SEM), also known as pathway analysis, to assess relationships between abiotic environmental factors, forest structure, forest health and productivity, and arthropod and bird abundance and diversity measures regardless of LiDAR categories.

List of Products

Presentations at Scientific Conferences:

- Hansen, C.F., P.G. Schaberg, G.H. Hawley, S.A. Rayback. 2013. Preliminary analysis of valley-wide growth trends for sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*) trees. Presentation at the HubbardEcosystem Study 50th Annual Cooperator's Meeting, West Thornton, NH, July 10th, 2013.

- Hansen, C.F., P.G. Schaberg, G.H. Hawley, S.A. Rayback, S.W. MacFaden. 2014. LiDAR remote sensing of forest canopy structure and its relationship to forest health and productivity and arthropod and bird diversity in a northern hardwood forest. Abstract submitted and accepted for presentation at the Hubbard Brook Ecosystem Study 51st Annual Cooperator's Meeting, West Thornton, NH, July 9th, 2014.

- Hansen, C.F., P.G. Schaberg, S. A. Rayback, G.H. Hawley, A.M. Strong, S.W. MacFaden. 2014. LiDAR remote sensing of forest canopy structure and its relationship to forest health and productivity in a northern hardwood forest. Abstract submitted and accepted for presentation at the 99th Ecological Society of America annual meeting, Sacremento, CA, August 14th, 2014.

Thesis:

- Hansen, C.F. 2015. LiDAR remote sensing of forest canopy structure: An assessment of the accuracy of LiDAR and its relationship to higher trophic levels. M.S. Thesis, University of Vermont.

Tangible Products:

- High-resolution LiDAR surface models: 1m resolution digital elevation model (DEM), 1m resolution normalized digital surface model (nDSM), and 1m resolution 0.5-10m above ground level (AGL) surface model.

Manuscripts under Review:

- Hansen, C. F., Schaberg. P. G., Strong, A. M., Rayback, S. A., and Hawley, G. J. Assessing tree health and productivity in a northern hardwood forest using LiDAR