Cracking the code of a northern forest carbon cycle: an integrated analysis using data, models and assessment of uncertainties.

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Project highlights: This study resulted in one of the most complete carbon budgets for a northern hardwood forest ecosystem. The timing of snowmelt and the abundance of diffuse solar radiation are important, but previously underappreciated factors affecting forest growth rates.

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http://www.nsrcforest.org

Project Summary

Understanding the carbon cycle in forests is important for a number of societal priorities related to climate change, resource management, and environmental policy. Despite decades of research, our knowledge of the carbon cycle is still hampered by large uncertainties and persistent challenges related to complex processes that are difficult to measure. In the Northern Forest region, scientists and decision makers share several needs related to forest carbon dynamics: (1) an improved ability to quantify the net balance between carbon uptake and loss (i.e. carbon sequestration), (2) knowledge of carbon fluxes within individual components of ecosystems and associated uncertainties, and (3) development of analytical tools that can be used to extend carbon cycle estimates through time and over diverse landscapes. Equally important is the need for an active exchange of information among scientists, stakeholders, and members of the public who are most closely tied to the region's forested landscapes.

The work conducted under this project addressed the needs listed above through a combination of focused field measurements, simulation model development, uncertainty assessment, and communication activities involving stakeholder groups and members of the public. Field measurements were conducted in a 100-125 year old forest stand at the Bartlett Experimental Forest in the White Mountains of New Hampshire and were designed to supplement CO_2 flux data from instruments mounted on a 110 ft. tower, established in 2004 as part of the North American Carbon Program. The resulting data set, which is likely the most complete carbon cycle dataset available for any research site within the region, yielded estimates of annual carbon sequestration of between 120 to 133 grams per m^2 using three different methods. In addition to common climate variables, variation in carbon uptake was related to the nitrogen content of tree foliage, the length of the vernal window—the time between soil thaw and leaf-out—and the fraction of incoming sunlight received as diffuse versus direct radiation. The most important sources of uncertainty involve belowground processes such as the amount and fate of carbon allocated to mycorrhizal fungi.

Our findings suggest that aging forests in the Northern Forest still represent a moderate carbon sink and that reducing uncertainties will require increased attention to belowground processes. The relevance of this research was discussed with several stakeholders and members of the public through a "science café" held at the Sea Dog restaurant and brewery in North Conway, NH.

Background

- Forests remove carbon from the atmosphere during photosynthesis and cycle it through living and dead plant tissues, symbiotic fungi, soil organic matter and respiration of CO_2 back to the atmosphere.
- The net difference between carbon uptake and the sum of all losses represents the total amount of carbon gained or lost by the ecosystem.
- Understanding the details of forest carbon cycling is important for a number of societal priorities related to climate mitigation, resource management, and environmental health.
- Although our overall understanding of the carbon cycle in forests has improved, reliable estimates of carbon sequestration are hampered by large uncertainties and difficulties of measuring complex processes in highly variable forested landscapes.

Background

- Eddy flux towers offer a sophisticated approach for measuring whole-ecosystem carbon exchange, but associated uncertainties are high and they don't provide estimates of individual carbon pools such as wood, soil organic matter, etc. These systems are often limited in number, given the expense and technical expertise needed to operate them.
- Forest inventory and biometric approaches are more cost effective and can be applied more widely, but building whole-system carbon budgets from individual component measurements is challenging and often requires that important pools such as soil carbon are ignored.
- One approach to reducing uncertainties and improving knowledge of mechanisms is to conduct detailed carbon budgets using a variety of methods in attempt to estimate uncertainties and reconcile methodological differences.

Project Goals

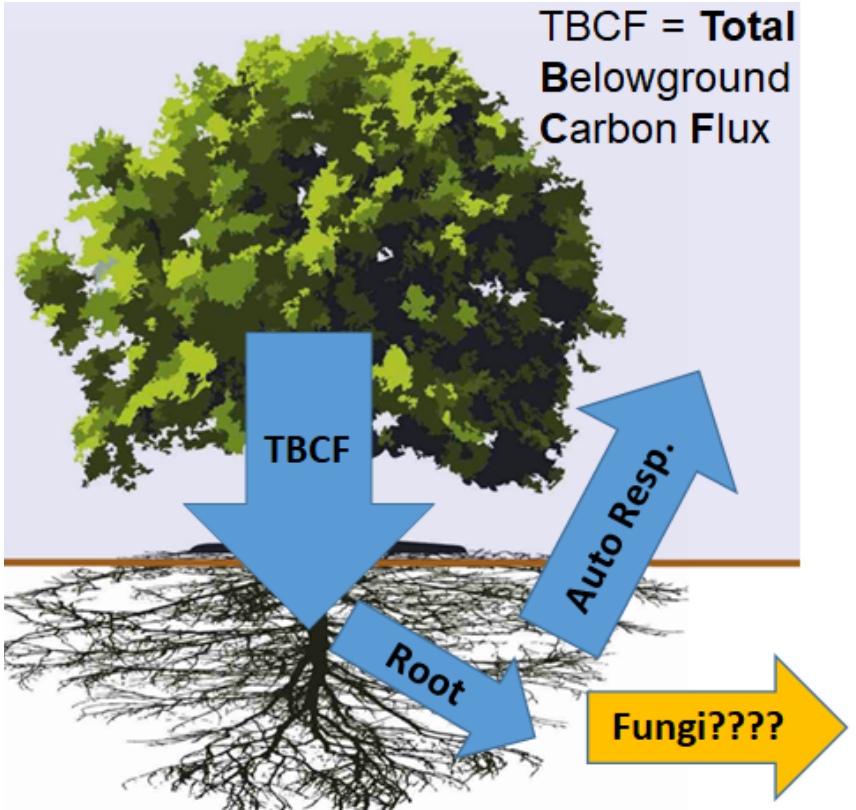
- The overarching goals of this project were to:
  - Advance state-of-the-art understanding of forest productivity and carbon cycling in the Northern Forest region.
  - Assess uncertainties and sources of error in carbon sequestration rates by comparing estimates derived through (a) eddy covariance, (b) biometric measurements of individual component fluxes, and (c) inventory approaches that examine changes in carbon pool sizes over time.
  - Enable more accurate projections across space and time through using forest simulation models and remote sensing.

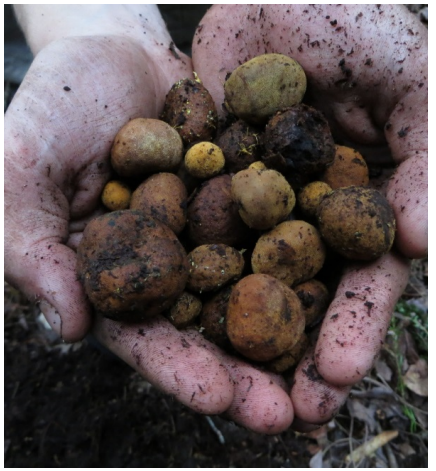
Methods: Eddy covariance

Eddy covariance flux towers with sensors located above the forest canopy measured the fluxes of carbon and water between forests and the atmosphere (top-down approach). These towers simultaneously recorded a suite of meteorological data which helped determine the climate drivers of ecosystem fluxes.

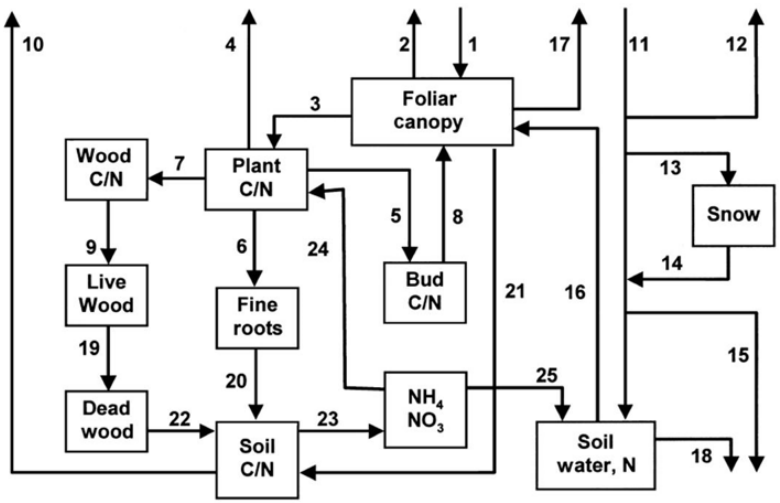
Methods: field measurements

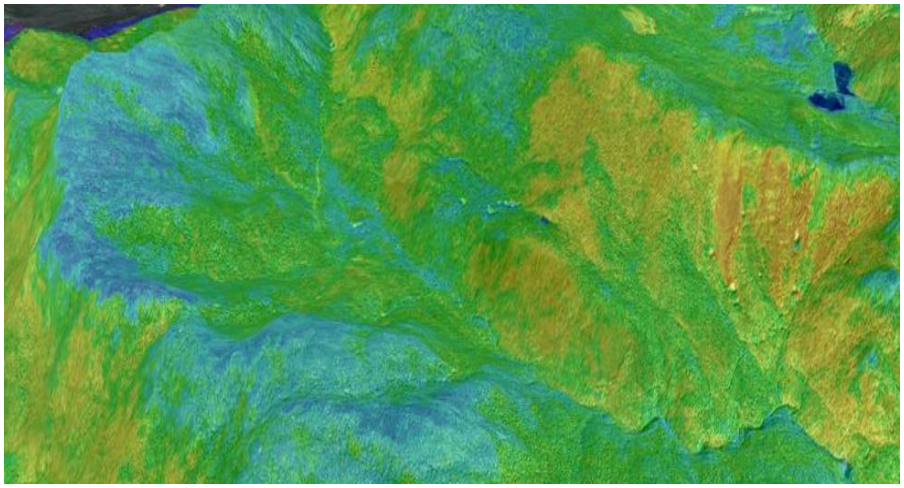
Long-term field measurements of individual component fluxes (bottom-up approach) were used to compile an ecosystem budget of carbon. By using multiple approaches over 15+ years, we quantified difficult to measure fluxes, such as the carbon allocated to symbiotic mycorrhizal fungi.





Methods: modeling and remote sensing





Field measurements were used to improve and parameterize a forest ecosystem simulation model, which can be used to extend carbon flux estimates across space (in combination with remote sensing) and time.

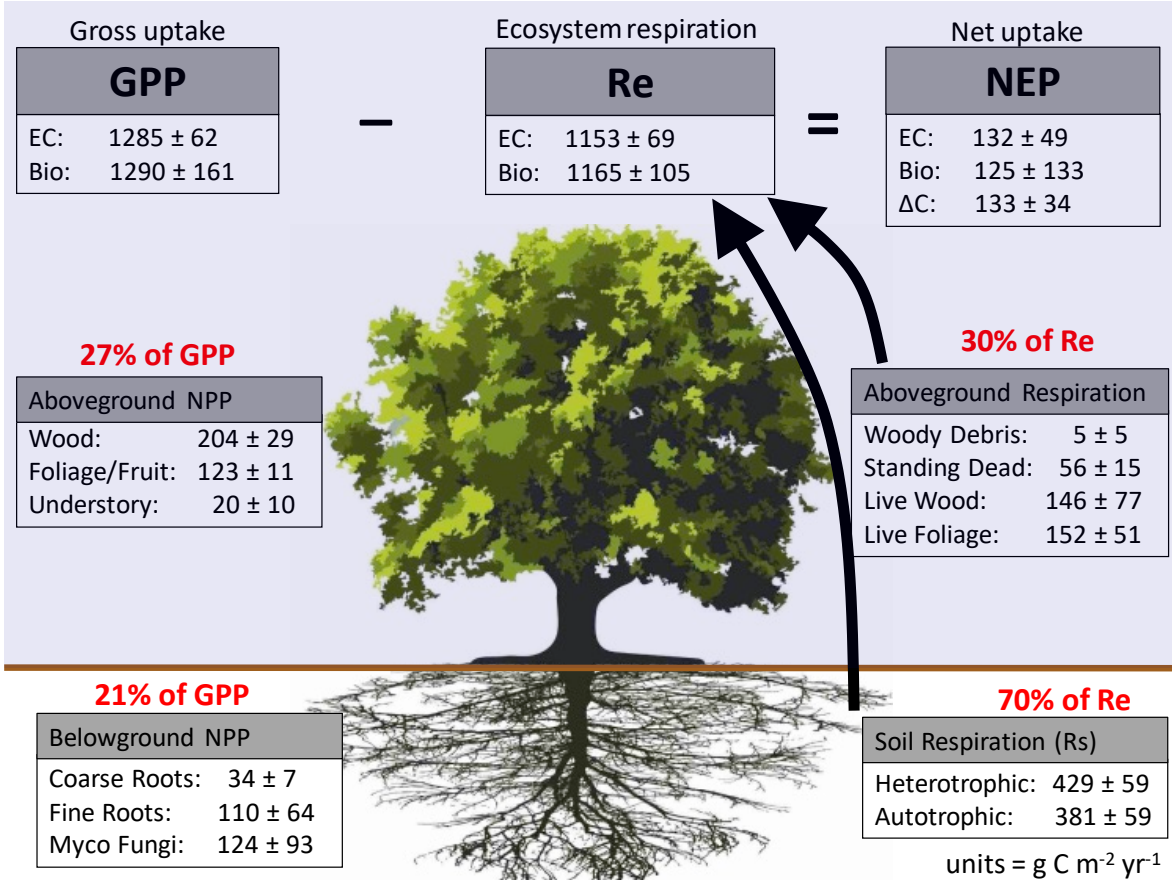
Results: Summary

Using long-term field measurements, eddy flux towers, forest ecosystem modelling, and remotely sensed canopy reflectance, we advanced our understanding and ability to predict northern forest growth, carbon dynamics, and response to climate. Specifically,

- One accomplishment of this project was to assemble a carbon budget of a northern temperate forest including uncertainty in estimated fluxes. Budgets such as these are difficult to compile, require multiple data streams over time, and are invaluable when assessing the validity and mechanisms in ecosystem models used to predict future forest growth.
- Multiple studies within this project also examined how forest growth and water use efficiency respond to soil nitrogen availability and species composition, rising atmospheric CO_2, and climate variables such as temperature, moisture, and the fraction of incoming diffuse versus direct sunlight.

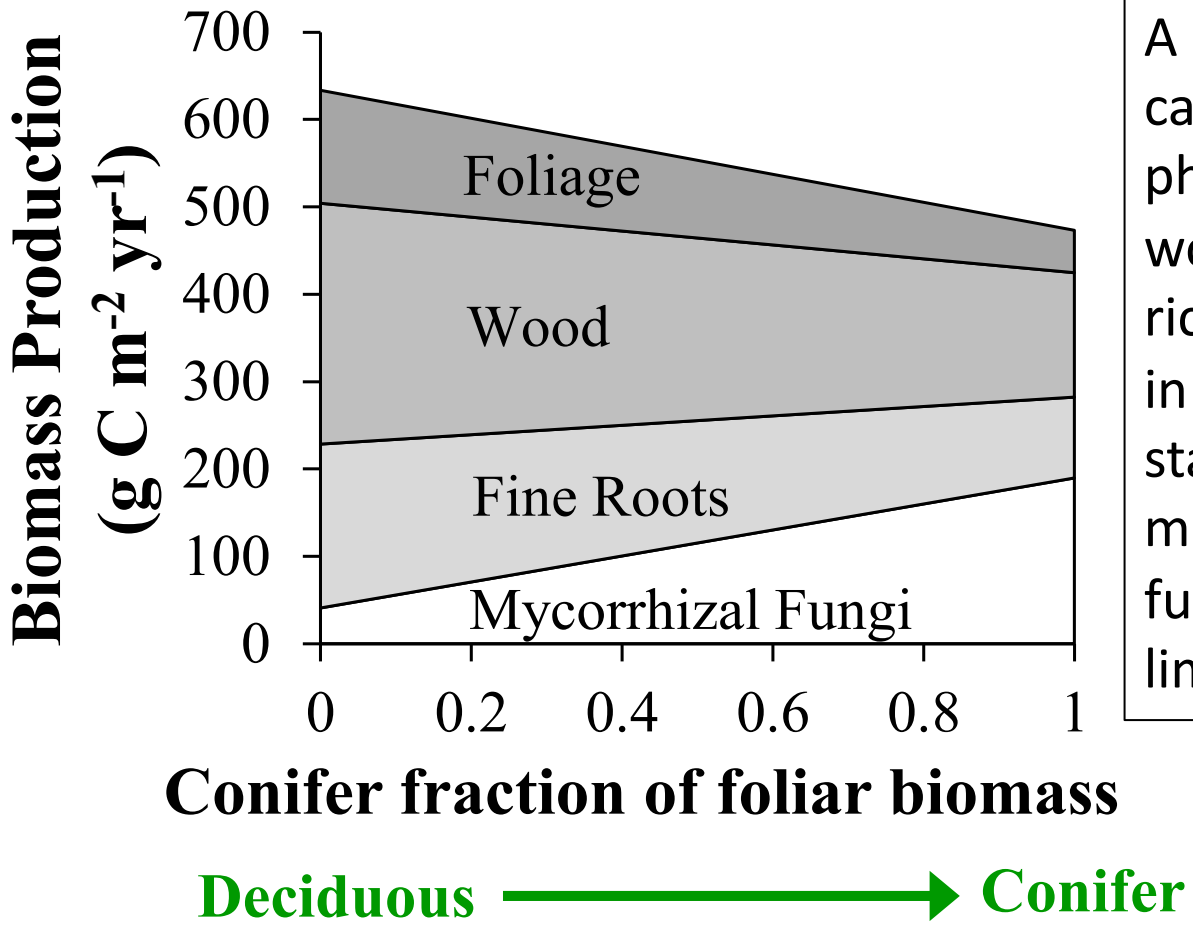
Results: Ecosystem carbon budget of a northern temperate forest

Compilation of an ecosystem carbon budget is invaluable for improving ecosystem models and predictions of future forest growth. The inclusion of uncertainty in our budget also highlights the forest components that are least well-constrained, and which should be the focus of future measurement efforts.



Ouimette et al. 2018

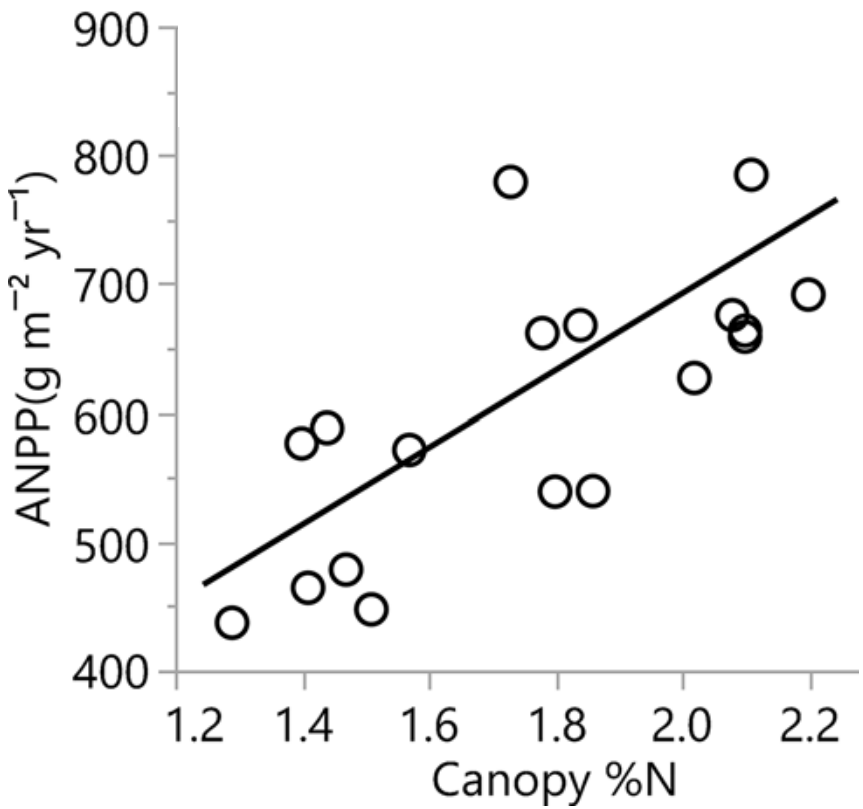
Results: Biomass growth of forest components varies with species type

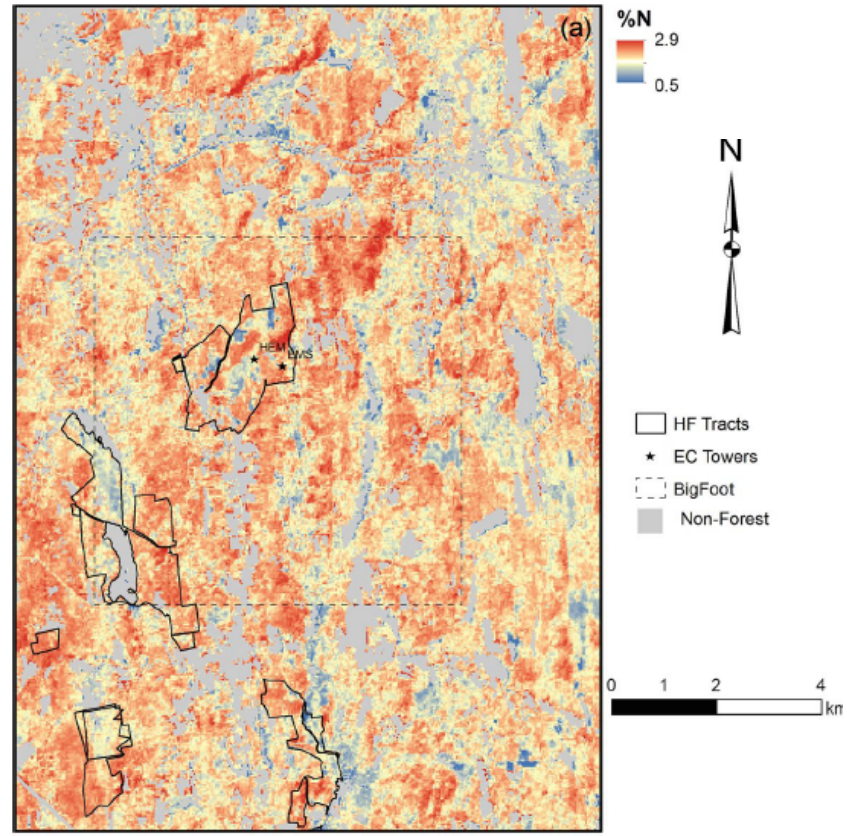


A higher proportion of carbon from photosynthesis is used for wood growth in nutrient-rich deciduous stands than in nutrient-poor coniferous stands where trees send more carbon to symbiotic fungi to acquire growth-limiting nutrients.

Ouimette et al. 2019

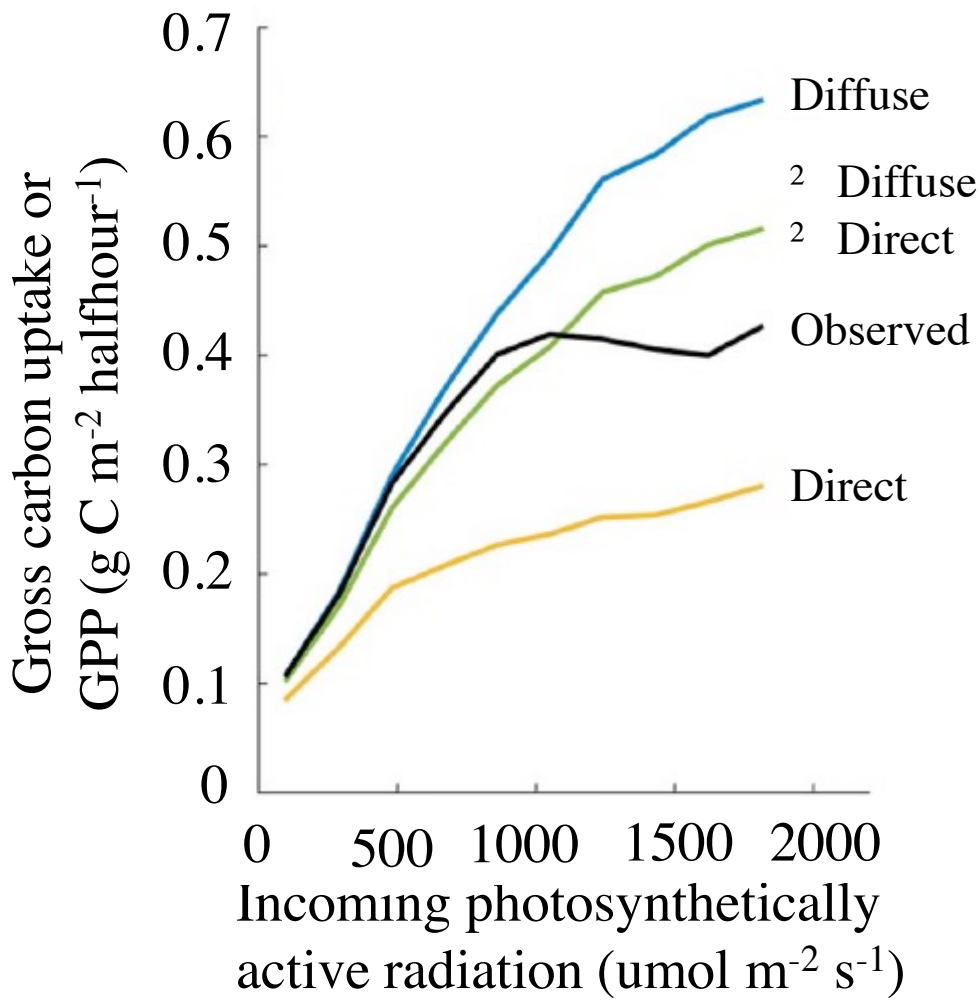
Results: Foliar %N offers the ability to improve estimates of forest growth





Using field data from a related study at Harvard Forest, we found a strong relationship between forest growth and canopy nitrogen (%N) (left). Remotely sensed canopy %N (right) was well correlated with field-measured %N and with patterns of land-use history. Our work reconfirmed that broadscale estimates of forest growth may be improved if remotely-sensed estimates of foliar %N were available. From Zhou et al. 2018

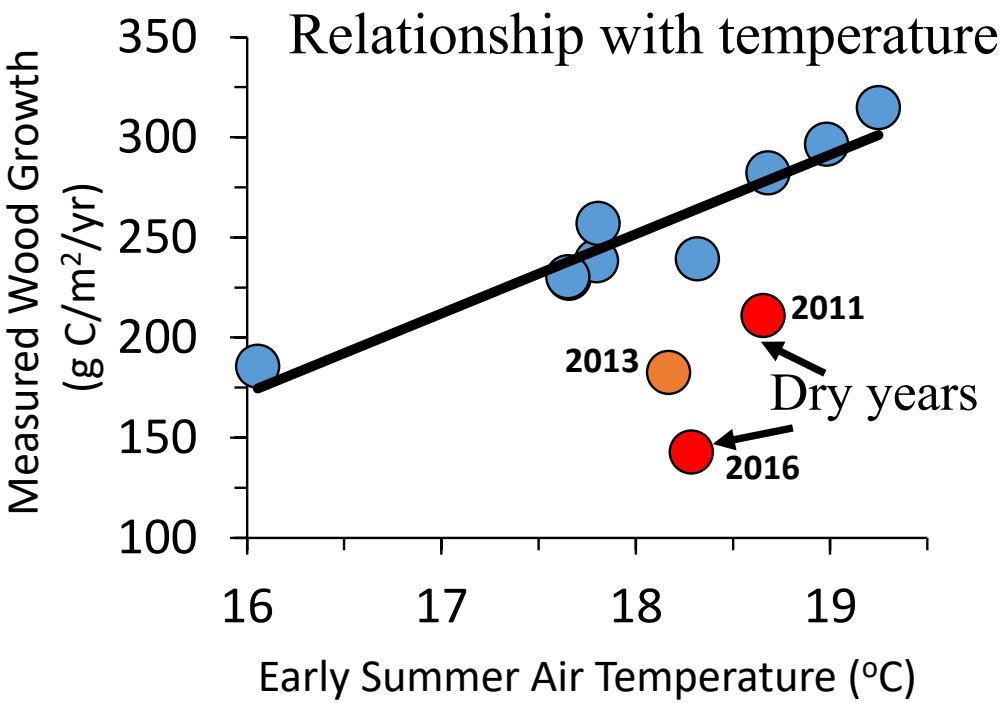
Results: The type of sunlight effects the efficiency of forest growth

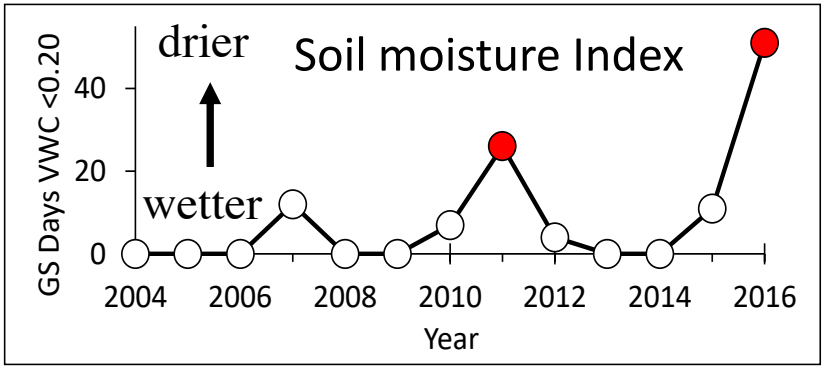


- Modeled gross carbon uptake (GPP) under direct, diffuse, mixed, and observed sunlight conditions across varying amounts of incoming solar radiation.
- Carbon uptake efficiency is enhanced under diffuse sky conditions compared to direct sunlight.
- Accounting for the effect of diffuse radiation on photosynthesis improves predictions of forest carbon uptake.

Lee et al. 2018

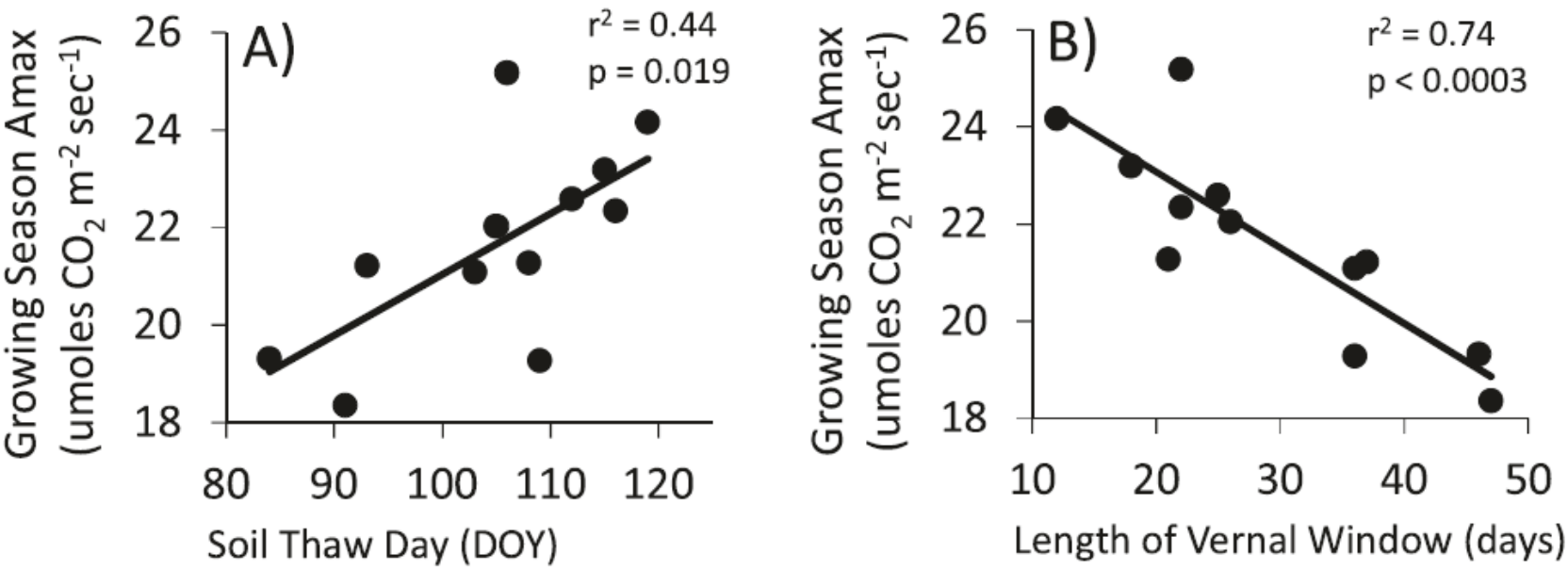
Results: interannual variation in wood growth is related to growing season temperature and moisture





Ouimette et al. 2018

Results: interannual variation in canopy photosynthesis is related to the timing of snowmelt and length of the winter-to-spring transition.



Ouimette et al. 2018

Results: The Forests and Climate science café series with residents of the Northern Forest region

A series of discussions led by 5 scientists on topics related to forest health and interactions with climate. Held at the Sea Dog Brewery in N. Conway, NH in March and April, 2016. Total attendance estimated at ~300

Implications and applications in the Northern Forest region

- The relatively close agreement between carbon flux estimates using eddy covariance, plot-level biometry and inventory approaches suggests that plot-level field measurements can be an effective way to assess carbon sequestration, provided below-ground processes can be included.
- The relationship between the timing of snow melt and canopy photosynthesis during the subsequent growing season suggests that carbon assimilation by northern hardwood forests may decline with climate change, given reductions in snowpack and a lengthening vernal window. The mechanism behind this is presently unknown and should be the focus of additional research.

Implications and applications in the Northern Forest region

- The increase in forest light use efficiency under conditions of diffuse sunlight suggests that forest growth models driven by canopy physiology can be improved by inclusion of direct vs diffuse radiation measurements.

- The most uncertain component of plot-based carbon fluxes involves belowground carbon allocation which emphasizes the need to include soils, root and symbiotic fungi in carbon budget estimates.

- Carbon allocated by trees to their symbiotic mycorrhizal fungi can represent up to 30% of total annual biomass production. The importance of this carbon pool increases with increasing dominance by evergreen tree species.

Future directions

Additional work should focus on:

- Improving the degree to which forest simulation models capture belowground processes and production of fungi.
- Understanding the mechanism through which conditions during the winter-to-spring transition influences canopy photosynthesis during the subsequent summer.
- Expanding measurements of, or developing methods for estimating, the ratio of direct to diffuse solar radiation.
- Examining errors in plot-based carbon budget estimates across a wider range of forest types and stand ages.
- Developing methods for remote sensing of foliar nitrogen concentrations that can be applied more broadly than

Products

Peer-reviewed Publications:

1) Guerrieri, R., Lepine, L., Asbjornsen, H., Xiao, J., Ollinger, S.V., 2016. Evapotranspiration and water use efficiency in relation to climate and canopy nitrogen in U.S. forests. Journal of Geophysical Research: BiogPeer-Reviewedeosciences 121, 2610–2629. https://doi.org/10.1002/2016JG003415

2) Guerrieri, R., Belmecheri, S., Ollinger, S.V., Asbjornsen, H., Jennings, K., Xiao, J., Stocker, B.D., Martin, M., Hollinger, D.Y., Bracho-Garrillo, R., Clark, K., Dore, S., Kolb, T., Munger, J.W., Novick, K., Richardson, A.D., 2019. Disentangling the role of photosynthesis and stomatal conductance on rising forest water-use efficiency. PNAS 116, 16909–16914. https://doi.org/10.1073/pnas.1905912116

3) Lee, M.S., Hollinger, D.Y., Keenan, T.F., Ouimette, A.P., Ollinger, S.V., Richardson, A.D., 2018. Model-based analysis of the impact of diffuse radiation on CO2 exchange in a temperate deciduous forest. Agricultural and Forest Meteorology 249, 377–389. https://doi.org/10.1016/j.agrformet.2017.11.016

4) Ouimette, A.P., Ollinger, S.V., Lepine, L.C., Stephens, R.B., Rowe, R.J., Vadeboncoeur, M.A., Tumber-Davila, S.J., Hobbie, E.A., 2020. Accounting for Carbon Flux to Mycorrhizal Fungi May Resolve Discrepancies in Forest Carbon Budgets. Ecosystems 23, 715–729. https://doi.org/10.1007/s10021-019-00440-3

Products

Peer-reviewed Publications (continued):

5) Ouimette, A.P., Ollinger, S.V., Richardson, A.D., Hollinger, D.Y., Keenan, T.F., Lepine, L.C., Vadeboncoeur, M.A., 2018. Carbon fluxes and interannual drivers in a temperate forest ecosystem assessed through comparison of top-down and bottom-up approaches. Agricultural and Forest Meteorology 256–257, 420–430. https://doi.org/10.1016/j.agrformet.2018.03.017

6) Toda, M., Richardson, A.D., 2018. Estimation of plant area index and phenological transition dates from digital repeat photography and radiometric approaches in a hardwood forest in the Northeastern United States. Agricultural and Forest Meteorology 249, 457–466. https://doi.org/10.1016/j.agrformet.2017.09.004

7) Zhou, Z., Ollinger, S.V., Lepine, L., 2018. Landscape variation in canopy nitrogen and carbon assimilation in a temperate mixed forest. Oecologia 188, 595–606. https://doi.org/10.1007/s00442-018-4223-2

Products

Theses:

Ouimette, A., 2017. Patterns and drivers of carbon fluxes in temperate forests. PhD Dissertation, University of New Hampshire

Madison, C. 2017. The photosynthesis-foliar nitrogen relationship in deciduous and evergreen forests of New Hampshire. MS Natural Resources, University of New Hampshire

Press coverage

This bud's for you: Science Pub Nights kick off at Sea Dog Brewing Co. March 31. The Conway Daily Sun, Saturday, March 26, 2016: pp. 1-3.

Studying the forests: Q&A with UNH'S Dr. Scott Ollinger. The Conway Daily Sun, Saturday, March 26, 2016: pp. 6-8.

Products

Data sets:

University of New Hampshire Earth Systems Research Center. 2016. Canopy Nitrogen, Bartlett Experimental Forest, NH USA, 2012. KNB Data Repository. doi:10.5063/F1V9860T.

Bartlett Experimental Forest CO2 flux data, hosted and distributed by AmeriFlux: https://ameriflux.lbl.gov/sites/siteinfo/US-Bar

Presentations (partial list)

Ouimette, A., S. Ollinger, A. Richardson, D. Hollinger, T. Keenan, L. Lepine, Z. Zhou. 2016. Comparison of carbon flux estimates using 10 years of eddy covariance and plot-level biometric measurements from the Bartlett Experimental Forest, New Hampshire. Poster presentation, AmeriFlux Annual Meeting, Golden, CO, September 21-23, 2016.

Ollinger, S.V. 2018. Forest Ecosystems and the Winds of Change: Forests as a Cog in the Earth System. Hubbard Brook Research Foundation special summer seminar, Hubbard Brook Experimental Forest, NH. Aug. 2018.