

A PUBLICATION OF THE NEW HAMPSHIRE  
AGRICULTURAL EXPERIMENT STATION

WINTER 2023

# INSPIRED

## 2023 FORESTRY RESEARCH REPORT



NH Agricultural  
Experiment Station

SCIENCE FOR THE PUBLIC GOOD

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## MESSAGE FROM THE DIRECTOR

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Dear members of the New Hampshire forestry community and beyond:

For 60 years, the New Hampshire Agricultural Experiment Station has supported research that helps New Hampshire manage forest land that provides our state and region with fuel for heating, wood to build and improve infrastructure, homes for a diverse wildlife population, and beauty to our landscapes that can be shared by our communities and with visitors. Today, Station scientists continue the strong tradition of developing research to inform how best to manage our forests in the face of rapidly changing climatic and economic conditions and to take advantage of existing opportunities, as well as to pioneer innovations that enable New Hampshire's forestry sector to lead long-term economic resilience and the environmental sustainability of our state.

The research briefs in this report cover a diverse set of issues and exciting opportunities for managing forests in the Granite State and northern New England. The topics include exploring management strategies to best integrate agricultural and forestry practices, gaining a better understanding of beech bark disease, assessing the viability of producing alternative syrups, using new aerial technologies for more cost-effectively measuring changes in forested lands, to name just a few. Each brief offers a snapshot of the rigorous science and practical takeaways that can make land managers more successful and, collectively, strengthen the Granite State through science.

As you learn about the research completed over the past several years, also know that there are always continued efforts underway. The science isn't always fast. It's never easy. But it always reflects the tenets that have made agricultural research at the New Hampshire Agricultural Experiment Station trusted for more than 130 years: addressing locally inspired questions, implementing rigorous and objective analysis and delivering data-informed recommendations that benefit our state, region and far beyond.

Thank you for supporting our efforts to improve the lives of every Granite Stater.



ANTON BEKKERMAN

Director, NH Agricultural  
Experiment Station

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# SCIENCE FOR THE PUBLIC

LOCALLY INSPIRED. GLOBALLY IMPORTANT.

The mission of your New Hampshire Agricultural Experiment Station (NHAES) is to ensure the resiliency of the Granite State's diverse communities and local

economies. For more than 130 years, we've served the state as the agricultural, food, natural resource and environmental research arm of the UNH land-grant mission. From the lab to the field, forest and sea, our researchers push scientific frontiers in pursuing sustainable food production and natural resource management across New Hampshire and beyond.

**High-Stakes Issues**  
**World-Class Science**  
**Sustainable Advancement**

New Hampshire is a state where forests abound. Close to 80 percent of the Granite State is covered by forest, serving as the lifeblood for plants, animals, people and communities. At the heart of NHAES research is a drive to anticipate challenges, find solutions and capture opportunities to better sustain and more effectively manage and enjoy these diverse ecosystems.



Matthew Vadeboncoeur collecting data at a field site in UNH Thompson Farm (left), Mark Ducey working with students at UNH College Woods (center), and a student taking tree measurements at UNH College Woods (right).



UNH's College of Life Sciences and Agriculture has a long history of managing forest properties across the state, including the 250-acre College Woods in Durham, the 188-acre Mendum's Pond in Barrington, and a 277-acre tract on Saddleback Mountain in Deerfield. Much of the research you'll read about was conducted on UNH-managed forest land and all of the work was supported through joint public funding from the USDA National Institute of Food and Agriculture and the State of New Hampshire.

All NHAES activities support the core institutional mission and goals of research, teaching and outreach for the Granite State. In addition to hosting approximately half of the 50 ongoing experiment station research projects, NHAES facilities provide opportunities for hands-on training for future scientists, support experiential learning for undergraduate students and offer space for public-private partnerships. The farms, dairies and greenhouses also host field days and are used by the UNH Cooperative Extension to engage with New Hampshire communities and communicate state-of-the-art knowledge.



# SILVOPASTURE: A CLIMATE-FRIENDLY ALTERNATIVE TO CONVENTIONAL OPEN PASTURE PRACTICES

H. ASBJORSEN, A. COBLE, A. CONTOSTA, K.A. JENNINGS, J. OREFICE, R. SMITH, A. STEWART AND M. VADEBONCOEUR

**T**he conversion of forests to agricultural land can have negative environmental consequences, such as increasing greenhouse gas emissions and decreasing the land’s resilience to disturbances due to extreme weather events. Agroforestry—the practice of planting trees and other woody plants with crops and/or livestock—may increase the climate mitigation potential of the land and its adaptive capacity. This could especially be the case when compared to conventional ‘open’ systems that normally lack woody plants and have relatively low plant diversity. This study monitored the effects of land-use changes for silviculture on greenhouse gas emissions, carbon storage and water dynamics.

## KEY TAKEAWAYS

Agroforestry systems such as silvopasture and forest farming may offer sustainable food production that aids climate change mitigation and climate adaptation.

Conversion of temperate forests in the northeastern United States to silvopasture results in lower greenhouse gas emissions compared to conversion to open pasture.

Silvopasture was shown to reduce soil greenhouse gas emissions by 35-50 percent, greater soil water dynamics and higher rates of annual tree growth.

## Is agroforestry suitable for New England?

Land use change, especially the conversion of forests to crop or pastureland, reduces carbon storage and increases emissions of greenhouse gases, diminishing the climate change mitigation potential of forested ecosystems. Moreover, the relatively low diversity and intensive management of most conventional agricultural systems can lead to adverse environmental impacts and lower resilience to disturbances, such as extreme weather or pest or pathogen outbreaks.

Land cover in the Northeast has changed several times over the past few centuries. The region experienced widespread forest clearing in the 18th century by European settlers, followed by farm abandonment in the mid-19th century and subsequent secondary forest regrowth. More recently, forest loss has occurred due to urban and suburban expansion. Less widely recognized has been the potential loss of forestlands to agriculture in response to a resurgence in demand for locally grown food. Additionally, population growth, economic development and climate change may further the trend of forest-to-agriculture conversion.

If such conversions continue to happen to the region's forestland—currently 60–80 percent of the total area—agroforestry could be a sustainable strategy. Agroforestry—which retains more trees and ecological functions within food production systems—can help mitigate the negative consequences of forest-to-agriculture conversion. For example, trees sequester and store more carbon than herbaceous plants and their extensive root systems contribute to nutrient cycling, soil stability and erosion control. Because trees take up more water than crops, they can also increase the water storage capacity of soil, which is important for regulating hydrologic flows and reducing flood risk.

Additionally, integrated agroforestry systems can have much higher biodiversity compared to typical agroecosystems. This biodiversity may confer greater resilience to disturbances and more stable productivity. Tree cover also provides shade that helps to stabilize microclimates, which can be important for both animal health and grass productivity during periods of high heat and low moisture common in late summers.

The Northeast is expected to experience more total, variable and extreme rainfall, and agricultural systems that offer both high carbon storage and hydrologic regulation services are critical to climate adaptation. But while previous research on agroforestry focused on tropical regions, knowledge of temperate agroforestry systems—such as those in the Northeast—is nascent.

## Measuring conversion of forests to silvopasture

One of the dominant agricultural practices in New England is the production of dairy and meat from cattle, which are often grazed on open fields. Silvopasture—the deliberate integration of trees, forages and livestock on grazed land—may offer a more climate sustainable alternative. Past research has assessed the climate benefits of incorporating trees into cultivated or grazed systems, but less work has been conducted into how removing trees affects greenhouse gas fluxes—the rate of exchange of gasses between the Earth's surface and the atmosphere—especially in the northeastern U.S. where such practices are relatively recent.

This research quantified the effects of converting forests to silvopasture—relative to converting forests to open pasture—on carbon dioxide (CO<sub>2</sub>) and nitrous oxide (N<sub>2</sub>O) emissions of the soil, retention of carbon and nitrogen in the soil and microclimate conditions. The work also assessed the response of silvopasture, open pasture and closed canopy forest ecosystems to an extreme drought that occurred in 2016.

A land-use change experiment was conducted at the University of New Hampshire's Organic Dairy Research Farm (ODRF) located in Lee, NH (**Figs. 1 and 3**), and collected measurements at a second similar experiment at the North Branch Farm in Saranac, NY (**Fig. 4**). Both experiments involved converting forest plots to either open pasture or silvopasture by removing all or a portion of the trees, and then comparing the response to these treatments with the conditions in unmanipulated reference forest and reference open pasture plots.

Measurements were collected over a 4-year period to assess meteorological conditions, such as air



**Figure 1.** Study design at the UNH Organic Dairy Research Farm, Lee, NH.

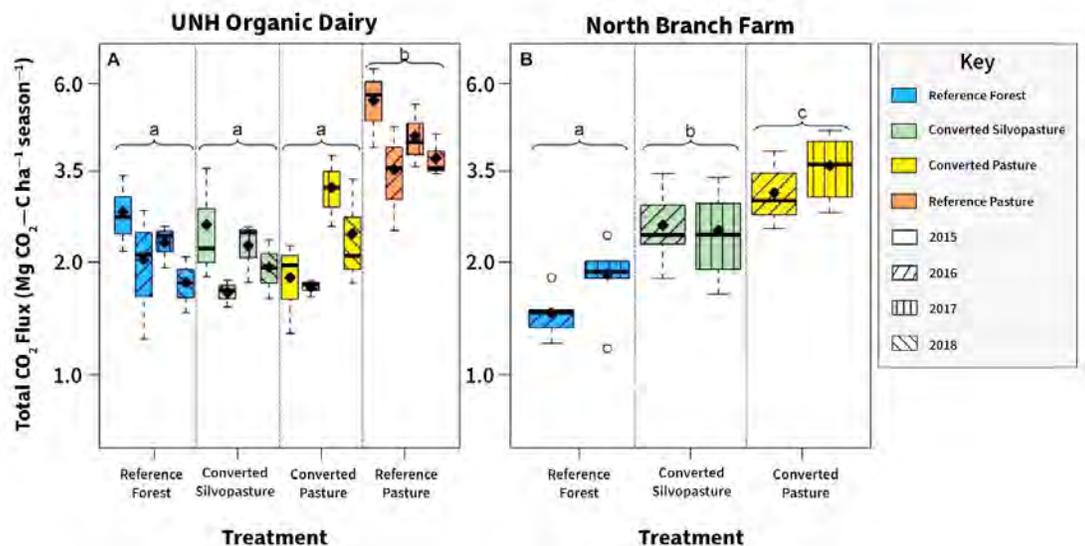
temperature, soil temperature and soil moisture, and soil greenhouse gas emissions. Carbon and water cycling were determined using tree growth (an indicator of carbon sequestration and storage) by collecting cores and measuring tree ring width and radial growth three years before and after the treatment.

Estimates of both inputs and outputs were used to quantify the effects of forest conversion on water balance. The primary input of water was throughfall—the amount of rainfall that reaches the soil surface because it is not intercepted by trees. The primary output of water was considered evapotranspiration—the process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants. This was calculated through a combination of direct measurements and modeling. Additionally, soil infiltration rates were determined for all treatment and reference plots to provide an indication of the effects of forest conversion on hydrologic functions, such as soil water storage capacity and flood control.

### A direction for climate resilient farming

Results from this study indicate that soil greenhouse gas emissions were generally lowest in the reference forests, higher in converted and reference open pastures and intermediate in silvopastures (**Fig. 2**). At the ODRF, growing season soil carbon dioxide emissions from the reference open pasture were approximately 50 percent greater than the other land use treatments, while emissions from the silvopasture were more similar to the reference forest. At North Branch Farm, soil carbon dioxide losses were 35-55 percent higher in the converted open pasture when compared to the other treatments, and the converted silvopastures exhibited intermediate values.

Similar patterns were observed in greenhouse gas emissions from the soil, including nitrous oxide that is 300 times as powerful as carbon dioxide at trapping heat in the atmosphere. Warmer air and soil temperatures and higher soil moisture availability



**Figure 2.** Total CO<sub>2</sub> flux from the treatment plots in response to forest conversion to silvopasture or open pasture at the UNH Organic Dairy Research Farm (ODRF) in Lee, NH, and the North Branch Farm in Saranac, NY.

recorded in both reference and converted open pastures likely contributed to higher greenhouse gas emissions exhibited by the open pastures.

Study results showed that silvopasture trees had higher rates of annual tree growth compared to the trees growing in the reference forest, especially for red oak and eastern hemlock, even during the drought year (2016). This suggests that lower tree densities in silvopasture may enhance forest resilience to water stress.

Water use by trees was significantly greater in white pine and red oak in the silvopasture compared to the reference forest during the drought year, also indicating higher drought resilience.

Total evapotranspiration in silvopasture was intermediate between forest (35 percent lower) and pasture (57 percent higher), which is consistent with silvopasture maintaining higher hydrologic regulation services compared to open pasture. Differences in soil infiltration rates across treatments also demonstrated the water storage potential of agroforestry systems. Overall, silvopasture had higher soil infiltration rates than open pasture, and these rates were more similar to conditions in the reference forest.

These results highlight the potential for silvopasture to ameliorate the negative climate consequences of forest clearing for agriculture in the northeastern U.S. and other temperate forested regions worldwide, offering a promising climate-resilient and environmentally sustainable food production system in New England.



**Figure 3.** Photos from UNH Organic Dairy Research Farm (ODRF), Lee, NH.



**Figure 4.** Photos from North Branch Farm, Saranac, NY.



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# THE CHALLENGE OF BALSAM FIR

M. DUCEY AND J. GUNN

In many parts of the country, the desirability and useability of trees helps to shape land management practices. In the northeastern U.S., decades of forest harvesting patterns have left some forestland with a deficit of desirable trees species. A series of analyses using U.S. Forest Service Forest Inventory and Analysis National Program data highlighted opportunities aimed at improving regional timber productivity and value by focusing on better species composition and individual tree quality. As part of these analyses, balsam fir (*abies balsamea*) was classified as a tertiary species, instead of a more desirable primary or secondary species. This research sought to identify reasons for this classification of the balsam fir and provide recommendations for land managers based on these reasons.

## KEY TAKEAWAYS

Balsam fir was classified as a tertiary species due to its modest timber value potential and susceptibility to fungal damage and spruce budworm.

In northern New England, balsam fir has been increasing in stocking, raising forest health concerns due to another impending spruce budworm outbreak.

Silviculture practices should consider preferential harvest of marketable balsam fir—either to make room for existing trees of more valuable species or to create large enough gaps for regeneration of a diverse mix of species.

This study grouped all tree species in New England and New York into four categories:

- Primary species preferred for commercial use, commanding the highest sawlog prices.
- Secondary species with consistent markets but lower sawlog prices.
- Tertiary species with sawlog markets but are compromised by forest health concerns, frequent defect or having only specialized markets.
- Non-commercial and non-native invasive species.

Generally, balsam fir is at best used for structural lumber, but most of the harvested resource goes to lower-priced pulp or biomass. Based on those factors alone, the species was not classified as a primary timber species.

Balsam fir is also notoriously shallow-rooted, meaning it is prone to windthrow—uprooting or overthrowing of a tree caused by wind—and fungal attack, especially if the roots have been damaged during earlier harvesting operations. It is also the preferred food of the spruce budworm (*Choristoneura fumiferana*), which has outbreaks on a roughly 40-year cycle. The next regional outbreak is already underway in Canada. Combined with its relatively low commercial value, these factors further move balsam fir from the secondary to the tertiary classification.

This study also examined trends in stocking across the region and over time, using a relative density measure developed in UNH's Ecological Forestry lab over a decade ago. The relative density measure accounts for how resources for growth are partitioned among species in a stand.

Balsam fir was one of the few species increasing in stocking over time in northern New England, supposedly as a rebound following the last major spruce budworm outbreak several decades ago. Increased balsam fir stocking levels should serve as a warning of potential forest health.

For most landowners, it makes sense to harvest marketable balsam fir preferentially. This would enable them either to free resources for the growth of existing trees of primary or secondary classification, or to create sufficiently large gaps for the natural regeneration of a diverse species mix.

A diverse species portfolio could include balsam fir, which possesses many positive non-timber attributes. For instance, it is a preferred species for Christmas trees in the region and for landscaping. However, because of its tertiary classification, it can be a riskier tree within a mixed species portfolio.

Property owners and land managers should pay attention to those stands where balsam fir is a major component of stocking and carefully plan the future of those stands.

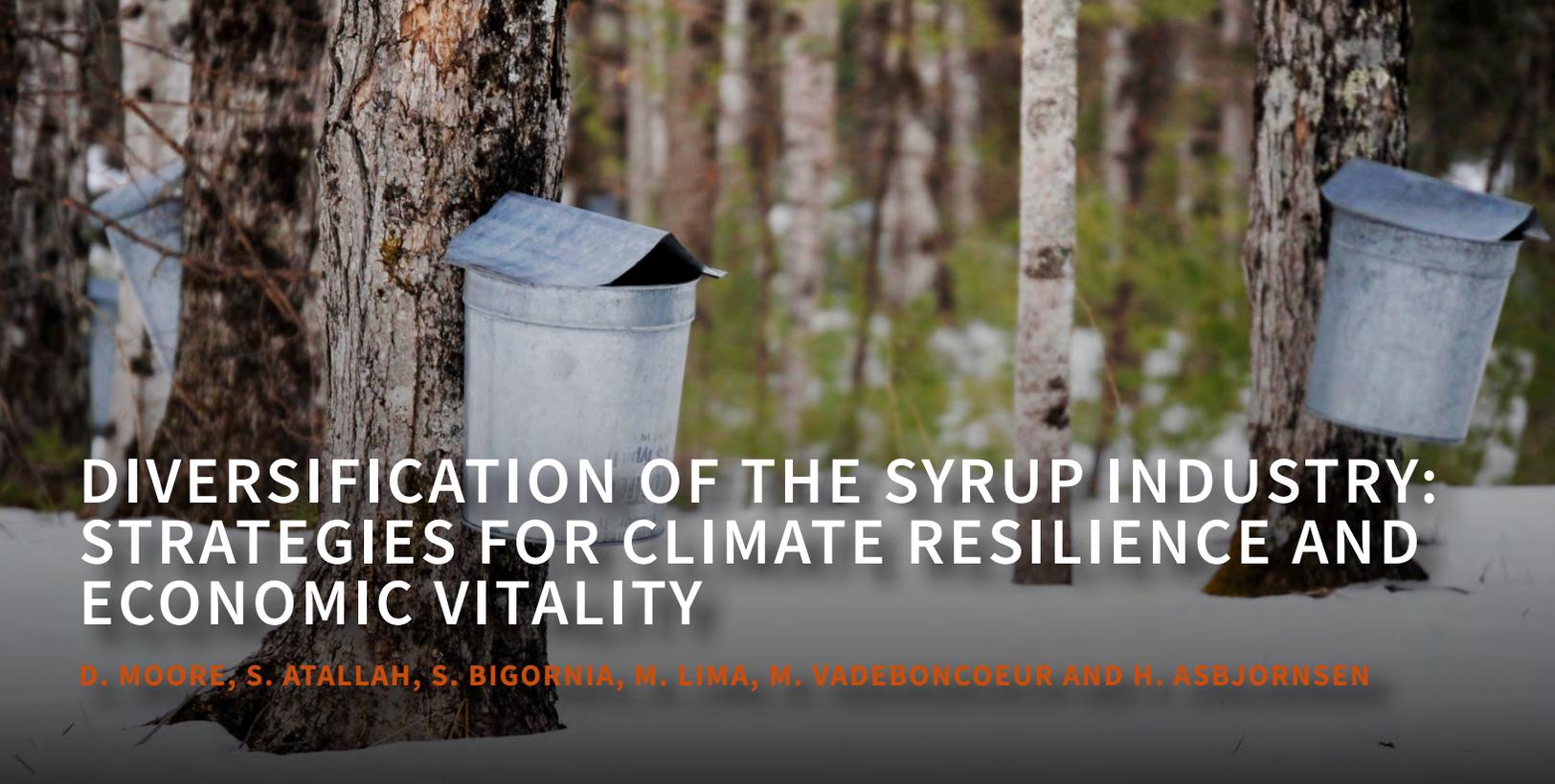


Forest stands dominated by balsam fir have lower potential for high-quality forest products and a higher probability of forest health concerns compared with stands dominated by quality trees of primary or secondary species. *Photo: M. Thompson.*



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# DIVERSIFICATION OF THE SYRUP INDUSTRY: STRATEGIES FOR CLIMATE RESILIENCE AND ECONOMIC VITALITY

D. MOORE, S. ATALLAH, S. BIGORNIA, M. LIMA, M. VADEBONCOEUR AND H. ASBJORSEN

**S**yrup production is an important agroforestry system in which sugarbushes—forests managed for syrup production—are actively managed to ensure large, healthy, sap-producing species such as sugar maple. While syrup is most commonly produced from maples, other types of trees can also be used. Novel syrups from birch and beech trees, for example, provide consumers with new flavors and new economic opportunities for producers. This research examines the potential for alternative syrup production in New England.

Syrup is most commonly produced from maples, but other types of trees can also be used. For example, there is a large birch syrup industry in Alaska and Canada, there are a handful of commercial walnut syrup producers in the U.S., and there is a commercial beech syrup producer in New York. These syrups are growing in popularity and typically sell for 4 to 6 times the price of maple syrup. Sugar maple has many advantages that make it particularly well-suited for syrup production but technologies developed to improve the efficiency of maple syrup production—

## KEY TAKEAWAYS

Expanding tree species diversity for syrup production may enhance climate resilience and adaptation because of the important ecosystem services provided by diverse tree communities.

Non-maple species show different syrup chemical properties and sap flow patterns compared to sugar maple, potentially creating opportunities for new markets and operational structures.

When consumers are provided with information about different tree syrups and the potential benefits of forest diversification, they are willing to pay more compared to consumers without this information.

such as vacuum pumps and reverse-osmosis filtration—have created possibilities for expanding to other species. Novel syrups provide consumers with new flavors and new economic opportunities for producers.

Maple syrup production is quintessential to New England's landscape, economy and culture, with historical roots as far back as the Native Americans and early European settlers. The industry is critical to sustaining vibrant local economies as well as the region's cultural identity, social fabric, and environment. In 2021, the maple syrup industry was valued at over \$84 million in the three northern New England states alone (Maine, New Hampshire and Vermont). However, because monocultures are inherently more vulnerable to uncertainties, the syrup industry's overwhelming reliance on the sugar maple species increases its risk of major damage from extreme climate events, interannual weather variability, pests, pathogens and market shocks, among others.

Northeastern U.S. forests support a high diversity of promising sap-producing deciduous tree species, yet very little is known about the sap flow patterns and yield potential of these trees, the quality or potential market value of their syrups or the sugarbush management and sap processing techniques they require. Research that identifies these aspects could promote greater climate resilience, economic vitality and sustainability. As a first step toward this goal, this research has focused on understanding sap flow and sap pressurization dynamics in these species during winter dormancy, evaluating the chemical properties of different saps and syrups and assessing consumer preferences and market potential.

## Syrup qualities and sap flow patterns

Data so far suggest that saps and syrups from non-maple tree species (birch, sycamore, beech, hophornbeam, basswood and alder) vary greatly in their chemical composition compared to sugar maple (**Tables 1** and **2**). For example, while sugar maple sap and syrup are dominated by sucrose, other species tend to produce saps and syrups that contain mostly fructose and glucose but very little sucrose. These differences in chemical composition have important implications for the processing of sap into syrup.

For instance, since fructose is known to break down at lower temperatures than glucose and sucrose, it may be important to limit the time that fructose-rich sap spends at high temperatures during processing. Reverse osmosis systems can aid in this process since they are used to concentrate sap without heat. Other qualities, such as phenolic content, can have positive implications for human health. Out of the five species included in the study, paper birch and American sycamore saps had the highest total phenolic contents, followed by American beech and sugar maple saps, and finally American hophornbeam sap.

Additionally, some species yield saps and syrups that are more acidic than those of sugar maples (**Tables 1** and **2**). Some acidic saps, like birch and sycamore, are known to dissolve many types of metals, which imparts metallic off-flavors to the syrups. One solution is to use only plastic, stainless steel and glass equipment to collect, store and process the saps and syrups from these trees. Another finding is that different tree species vary in the timing of their sap flow. For example, saps from American beech and London planetree—a

**Table 1.** Refractive index, pH and sugar concentration data for sap samples collected during winter dormancy between 2020 and 2022 in New Hampshire.

| Species              | Latin Name                   | Mean Refractive Index (Brix) | Mean pH | Mean Fructose Concentration (mM) | Mean Glucose Concentration (mM) | Mean Sucrose Concentration (mM) |
|----------------------|------------------------------|------------------------------|---------|----------------------------------|---------------------------------|---------------------------------|
| Sugar maple          | <i>Acer saccharum</i>        | 2.6                          | 7.2     | 0                                | 4                               | 56                              |
| Paper birch          | <i>Betula papyrifera</i>     | 0.7                          | 6.8     | 21                               | 7                               | 0                               |
| American beech       | <i>Fagus grandifolia</i>     | 0.6                          | 7.3     | 10                               | 13                              | 0                               |
| American sycamore    | <i>Platanus occidentalis</i> | 0.8                          | 6.4     | 12                               | 11                              | 0                               |
| American hophornbeam | <i>Ostrya virginiana</i>     | 0.3                          | 7.0     | 4                                | 6                               | 0                               |
| American basswood    | <i>Tilia americana</i>       | 0.3                          | 6.9     | no data                          | no data                         | no data                         |
| Alder                | <i>Alnus spp.</i>            | 0.7                          | 7.2     | 13                               | 16                              | 0                               |

**Table 2.** Sugar and pH concentration data for syrup samples produced from sap samples collected during winter dormancy between 2020 and 2022 in New Hampshire

| Species              | Latin Name                   | Mean pH | Mean Fructose Concentration (mM) | Mean Glucose Concentration (mM) | Mean Sucrose Concentration (mM) |
|----------------------|------------------------------|---------|----------------------------------|---------------------------------|---------------------------------|
| Sugar maple          | <i>Acer saccharum</i>        | 5.9     | 5                                | 10                              | 1465                            |
| Paper birch          | <i>Betula papyrifera</i>     | 4.7     | 1510                             | 638                             | 13                              |
| American beech       | <i>Fagus grandifolia</i>     | 4.7     | 1015                             | 1230                            | 5                               |
| American sycamore    | <i>Platanus occidentalis</i> | 3.5     | 1015                             | 1263                            | 5                               |
| American hophornbeam | <i>Ostrya virginiana</i>     | 5.1     | 755                              | 1015                            | 85                              |
| American basswood    | <i>Tilia americana</i>       | 5.3     | 650                              | 740                             | 0                               |
| Alder                | <i>Alnus spp.</i>            | 4.8     | 1215                             | 1585                            | 5                               |

hybrid sycamore (*Platanus x acerifolia*)—flow when temperatures cross the freeze-thaw threshold, such as maple sap. However, hophornbeam and birch have sap flows that occur later in the spring. Managing sugarbushes that include species with different sap flow patterns can be advantageous because resources, labor and expertise can be distributed across a longer time period and potentially used more efficiently.

Lastly, preliminary results show that saps from trees other than maples are much more diluted than sugar maple sap. As such, reverse osmosis systems will likely play an important role in their production.

### Market potential of a more diverse syrup industry

Syrups produced from different tree species differ in flavor and, therefore, determining the perceived quality and taste preferences of different syrups among consumers and their willingness to pay for these syrups is important for assessing potential future market value. Results suggest that when consumers are provided with information about both the type of tree syrup they are tasting and the potential benefits of forest diversification, they are willing to pay \$1.10

more per 12.7-oz bottle compared to consumers who did not receive this information. Therefore, consumer preferences might support the future diversification of sugarbushes, especially if labeling can successfully communicate the ecological benefits of forest diversification. Since overall consumer willingness to pay was still highest for maple syrup, producers may consider syrup blends that combine the taste benefits of maple syrup and the ecological benefits of diversified sugarbushes for promoting climate resilience.

Ongoing research is analyzing the saps and syrups extracted from different non-maple tree species to better understand their chemical properties and potential health benefits. For example, foods with high phenolic compound content like maple syrup have been shown to have multiple health benefits, including being anti-inflammatory and anti-carcinogenic. Current hypotheses are that some non-maple syrups may yield phytochemical profiles with implications for consumer health. The research will also assess the degree to which diversification of the syrup industry can contribute to promoting greater climate resilience for both ecosystems and local communities.



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# IMPACTS THAT MATTER

FROM THE SEACOAST TO  
SCIENCE FOR SUSTAINABLE

THE NORTH WOODS,  
LIVES & LIVELIHOODS

## Research Cornerstone

For more than 130 years, the NHAES has served the Granite State to provide research for critical questions that increase food security and environmental health.

## High-stakes Issues

We provide science-based answers to critical issues in New Hampshire: resilient food production, effective forest management and sustainable natural resources for future generations.

## World-class Science

Our research pushes scientific frontiers and develops data-informed solutions to help the economic, environmental and societal well-being of New Hampshire's many diverse communities.

## Economic Driver

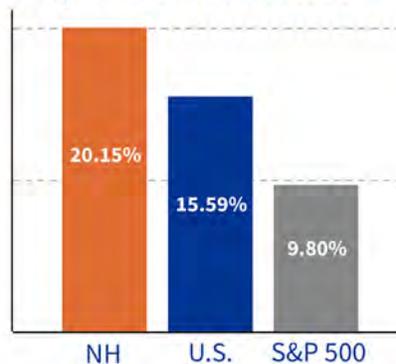
Growing innovative private-public partnerships, training tomorrow's work force and providing new technologies and knowledge that grow small business success.

## BY THE NUMBERS

The Experiment Station Supports:

|           |   |
|-----------|---|
| 52        | Scientists                              |
| 38        | Graduate students, postdoctoral fellows |
| 810       | Research farm and forest acres          |
| 304       | Research dairy cows                     |
| 1,395,231 | Stakeholders across New Hampshire       |

Annual Rate of Return on Agricultural R&D Investment



Source: Data from Plastina (2012), "Rates of return to public agricultural research in 48 states."

# \$23.8 million

in competitive federal, state, and industry grants awarded to Station scientists to further support locally important research.

A nearly 400% return on initial federal and state investment.



# EXAMINING BEECH BARK DISEASE: FUNGAL PATHOGENS AND BARK RESPONSES

J. GARNAS, E.W. MORRISON AND K. WINDSTEIN

**B**eech bark disease (BBD) is a widespread-cankering disease of American beech (*Fagus grandifolia*) caused by invasive felted beech scale insects feeding on the trees and the subsequent infection by specific fungal pathogens. While the disease does kill trees, beech remains an important part of the forest ecosystem, even after many decades of infection. Despite over a century of research on this important forest disease, scientists still lack a precise understanding of the contributions of two fungal pathogens to the progression of the disease and the role of the felted beech scale in initiating BBD. The goal of this research was to understand how the fungal pathogens in the BBD system are currently distributed across the full range of this disease and how beech tree bark responds to insect and pathogen attack.

## KEY TAKEAWAYS

The pathogen *N. ditissima* occurs more broadly than previously understood, observed in 9 of 10 sites measured and in 31 percent of trees.

Evidence also suggests *N. faginata* is adapting to warmer climate patterns as it disperses into more southern regions.

Beech scale insect establishment rates are lower on large, smooth beech trees and on rough-barked trees of any size, while small smooth trees are more susceptible.

## Fungal pathogens: *N. faginata* and *N. ditissima*

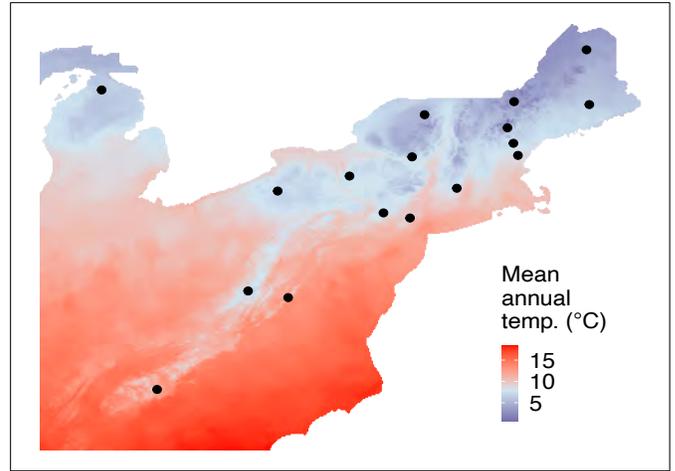
Beech bark disease is caused by the combined damage from the felted beech scale insect (*Cryptococcus fagisuga*) (Fig. 1) and then infection by two presumptively native fungal pathogens (*Neonectria faginata* and *Neonectria ditissima*) (Fig. 1). Surveys based on fruiting body (perithecia) collections have suggested that *N. faginata* is the dominant and more aggressive pathogen, to the point of completely excluding *N. ditissima* in many stands in the aftermath forest. However, differences in the timing and conditions under which either species produce fruiting bodies may bias these disease measurement methods.

In a study of both fungal pathogens, amplicon-sequencing surveys of the whole communities of fungi present in the bark of 102 beech trees across 10 sites were used to quantify occurrences of *N. faginata* and *N. ditissima*. This approach avoided potential bias inherent to fruiting body surveys. Data were also collected on perithecia from 17 sites across a range of climate conditions (Fig. 2) to examine population structure and potential adaptation to different climates. Bark samples were collected using a sterile hollow steel punch for both amplicon-sequencing and population genomics sampling. Single-spore isolations were performed from perithecia to generate a collection of fungal individuals across the range of BBD for subsequent population genomic and culture-based growth assays.

While *N. faginata* was generally more prevalent than *N. ditissima* in sites in aftermath forests, *N. ditissima*



**Figure 1.** American beech trees infested with the beech scale, as indicated by white-colored wax masses (left); or colonized by *Neonectria* fungi, as indicated by masses of red-colored perithecia (right).



**Figure 2.** Sampling locations (black points) for *Neonectria* population genetics sampling distributed across a natural climatic gradient as indicated by mean annual temperature.

occurred more broadly in these forests than was previously suspected. *N. ditissima* was observed in 9 of the 10 sites examined and was more prevalent (two sites) or as prevalent (one site) in the three northernmost sites (Maine, Michigan and Wisconsin). The two species co-occurred in many of the trees examined, including in 27 percent of all trees (both asymptomatic and symptomatic) and 36 percent of symptomatic trees. At least one of the pathogens was detected in 55 percent of the 60 bark plugs that had no perithecia present on the periderm surface. Together, these results suggest that *N. ditissima* may play a greater role in disease progression than previously understood in aftermath forest stands.

### Possible climate adaptation and southward spread

Joint species distribution modeling was used to examine how species occurrence related both to climate—heat accumulation during the nongrowing season of American beech—and to different measures of disease severity, including the level of crown dieback and canker abundance.

The results indicated divergent associations with climate for the two pathogens. *N. faginata* was positively associated with beech growing degree days, while *N. ditissima* displayed a negative association. Population genomic analyses also revealed potential climate adaptation in *N. faginata* populations.

Overall, *N. faginata* displayed a signal of genetic isolation by distance and little evidence of historically isolated subpopulations. The historical distribution and, in fact, the original host of this fungus prior to its novel association with beech is unknown. The lack of

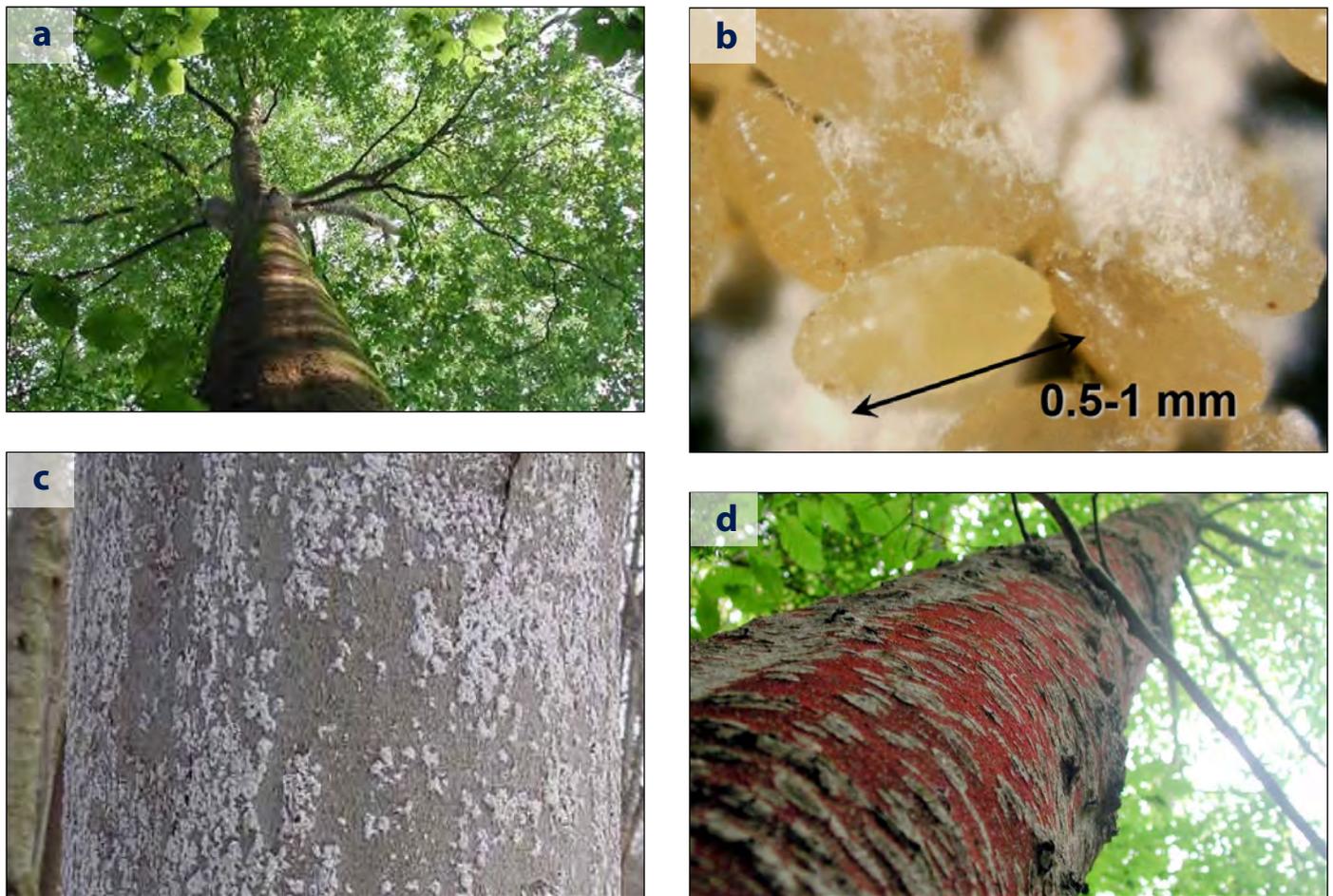
population substructure provides important evidence that *N. faginata* has dispersed in conjunction with the relatively consistent spatiotemporal spread of the beech scale, rather than having colonized beech multiple times from across an existing range. Analyses of genomic data indicate an evolutionary adaptation to warmer temperatures in *N. faginata*. This supports the hypothesis that there was a single-colonization event in Nova Scotia, Canada, followed by spread from cooler to warmer climates.

In total, 182 mutations were associated with non-growing season heat accumulation, with 76 of these occurring in or near one of 34 genes showing evidence of adaptation to climate. While population genomics analyses are ongoing, these initial results provide strong evidence of rapid evolution to warmer climates, which has obvious implications for the ability of *N. faginata* to adapt to a warming planet.

### The role of the felted beech scale

The felted beech scale is a tiny, pale orange, wingless insect (**Fig. 4b**). Only females are known of this species, and they are legless at maturity. Their sole appendage is a straw-like feeding tube called a stylet that they plunge into the surface bark layers of their host tree, the American beech. They are most visible by the white felty wax that they produce, common on the trunks of many beech trees in this region (**Fig. 4c**).

The felted beech scale was introduced from eastern Europe into Nova Scotia, Canada, in 1890, spread through New Hampshire in the mid-20th century and is now present in a little over half the range of beech. Populations can become super-abundant, “white-washing” trees from top to bottom with the waxy exudates. Perhaps more importantly, however, the beech scale serves as the initiating agent of BBD,



**Figure 4.** (a) Field photos of a healthy American beech (*Fagus grandifolia*) tree with a rough bark phenotype that is unfavorable to scale insect establishment; (b) invasive felted scale insect adults, one of the causal agents of beech bark disease, with white wax removed; (c) a smooth-barked, “white-washed” tree, indicating a very high scale insect establishment; and (d) bright red perithecia fungal spore-producing structures covering a highly infected beech tree.

which is caused by this insect along with *N. faginata* and *N. ditissima*.

Feeding by scale insects facilitates access to the phloem—the vascular tissue in plants—for one or quite often both types of pathogenic fungi, resulting in localized infections called cankers. BBD is responsible for elevated rates of mortality among adult beech; for the pockmarked and/or contorted form of many American beech trees that remain; and, surprisingly, for the proliferation of smaller, denser, beech-dominated stands in eastern North American forests.

### Complex interactions among BBD agents

After well over a century of study, there are still many mysteries around this disease complex. Current research is examining how the scale insects and fungi influence one another's populations in the “aftermath” forest, where BBD has become endemic.

One hypothesis is that the nature of the interaction between the beech scale and *Neonectria* fungi may have switched from one of facilitation or mutualism—during the early stages of invasion—to antagonism, and that this switch is largely mediated by bark responses of the host tree. This could explain the apparent decline in disease severity and population growth rates of BBD causal agents in long-infected forests.

To test this hypothesis, data were collected from an experiment that established small populations of insects and fungi at different densities and in different combinations on over 80 host trees and measured establishment rates for insects, lesion growth of fungal infections and host tree response to both.

Results indicate high levels of variation among individual beech trees in both scale insect establishment rates and fungal infection consistent with the expected range of genetic susceptibility to BBD, although variation in responses to fungal infection requires further study. Trees that had rough bark at the initiation of the experiment (50 percent

of the sample) had significantly lower rates of scale insect establishment. Since rough bark is in large part a response to prior BBD infection, this represents a key negative feedback in the development of the disease. Interestingly, scientists found elevated scale insects on smooth bark trees, but only those in the smaller size class (10-20 cm diameter at breast height). Larger trees that maintain smooth bark are likely genetically resistant to scale attack; rates of establishment on these trees resembled that on rough barked trees of either size class.

Bark lesion growth varied by fungal species, with *N. faginata* producing the largest lesions while eliciting the weakest host response. *N. ditissima* produced the smallest lesions and the largest host response. Sites that were co-inoculated with both fungi showed intermediate growth. *N. ditissima* responded negatively to local scale insect presence, but only on rough bark trees. *N. faginata* responded slightly negatively across rough and smooth bark types. At a minimum, this suggests that at this local spatial scale, insect feeding does not facilitate *Neonectria* growth and may in fact suppress lesion development. This offers new clues for understanding the epidemiology of this important forest disease.

### Where to now?

Experimental field manipulations designed to uncover key mechanisms driving beech bark disease, and forest disease more generally, is critical to enhancing understanding and to informing management. One implication of this work is the two fungi involved in BBD clearly behave differently as they influence the disease cycle and so need to be differentiated in future studies. Luckily, this has been made much simpler by the availability of low-cost genetic screening and development of specific molecular probes for use in the BBD system. Furthermore, screening for host resistance in American beech should include consideration of the fungal pathogens and bark responses therein, which research has shown can be an important driver of BBD development over time.



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# HOW RESILIENT ARE NEW HAMPSHIRE'S FOREST ECOSYSTEMS AND TREE SPECIES TO DROUGHT?

H. ASBJORSEN, M. VADEBONCOEUR, Z.C. BERRY, A. COBLE, K. JENNINGS AND C. MCINTIRE

**C**limate change is expected to bring a warmer, wetter and more variable climate to the Northeast, including more frequent and severe droughts. Despite the potential wide-ranging implications of drought on forest health and ecosystem services, little is known about the capacity of different northeastern tree species to respond, adapt to and survive. This study considered how dominant tree species vary in their sensitivity and response to moderate and extreme drought. The research helped provide the first assessments of physiological and soil moisture thresholds that lead to abrupt changes in tree species' response to drought and how the species vary in their ability to recover growth and function after a drought.

## KEY TAKEAWAYS

Simulated major drought conditions showed that dominant northeastern tree species are sensitive to moisture stress but differ in drought survival strategies.

White pine trees avoid damage from drought by quickly closing their stomata to reduce water loss, which may help them survive longer drought periods but significantly reduce growth.

Oaks limit drought impacts by accessing deeper soil water, continuing photosynthesis and taking longer to lose water while in drought, but may be more vulnerable to severe droughts.

## Simulating drought

Humid temperate regions around the world are expected to become simultaneously wetter (greater mean precipitation) and drier (more prolonged droughts), and climate patterns in the northeastern U.S. over the past century already reflect these trends. Recent severe summer droughts have occurred in southeastern New Hampshire in 2016 and 2020.

While reports of massive tree mortality as a result of drought are rare for this region, scientists also lack a sound understanding of the sensitivity and response of these temperate forest ecosystems to extreme drought. Given the key role of northeastern forests in carbon storage and in providing a range of ecosystem services to society, improving understanding of drought effects on these forests is critical to predicting future change and to managing forests for climate adaptation.

Two important indicators of drought response include how species regulate their stomates—small pores on the leaf surface that allow carbon dioxide in for photosynthesis and release water into the atmosphere—and woody stem growth—an integrated measure of how physiological responses affect productivity. The occurrence of thresholds—or abrupt changes in ecological response to a stressor—also provide a useful framework for understanding drought interactions. This information can help inform forest management practices to promote more climate resilient and adaptive forest ecosystems in the future through, for example, the application of thinning treatments and assisted migration plantings.

To better understand the effects of drought on northeastern forests, a drought experiment (**Figs. 1 and 2**) was established in 2016 at UNH's Thompson Farm to simulate an extreme drought event by removing 50 percent of the throughfall rain for at least four growing seasons. Data were collected for soil moisture, tree diameter growth, litterfall, leaf gas exchange, sapflow (a measure of tree water use, or transpiration), stable isotopes of carbon (an indicator of water use efficiency) soil nutrients, decomposition, fine root production and soil respiration. The first year of the experiment coincided with the 2016 extreme drought, which was the driest summer since 1997. When this natural drought was superimposed on the throughfall exclusion, it created the most extreme drought experienced by these trees in their lifetimes.

### Species-based response to drought

Results show that while both species—white pine (*Pinus strobus*) and red oak (*Quercus rubra*)—significantly



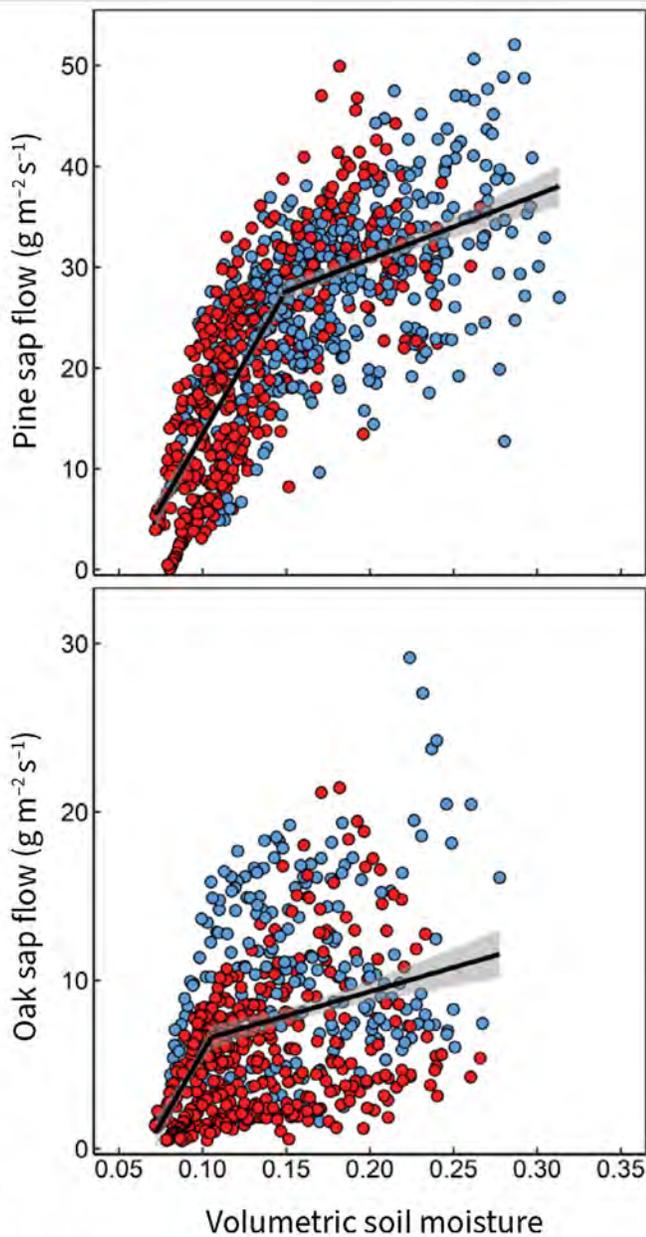
**Figure 1.** A precipitation throughfall removal experiment used to simulate a once-in-a-century drought at UNH's Thompson Farm in Durham, NH.



**Figure 2.** Emily Perry '19 labels and bags a red oak branch sample to be brought back to the laboratory from one of the Thompson Farm throughfall exclusion plots.

reduced their water use in response to increased moisture stress, white pine exhibited greater stomatal sensitivity, sharply reducing its water uptake in response to soil drying. This is reflected in the different soil moisture thresholds that triggered strong stomatal closure (measured as reduced sapflow at the daily time scale) in each species: 14 percent and 10 percent soil moisture content for pine and oak, respectively (**Fig. 3**).

Across study years, a strong linear relationship between water-use efficiency (WUE) and precipitation for pine was discovered. The species begin conserving water when soils are not yet very dry. In contrast, the WUE and precipitation relationship for oak is nonlinear, with WUE becoming significantly lower only when severe moisture stress occurred during the 2016 drought. This is consistent with a strategy of allowing leaves to reach low water potentials that risk hydraulic damage, and only reducing photosynthesis in order to conserve water when soils become very dry.

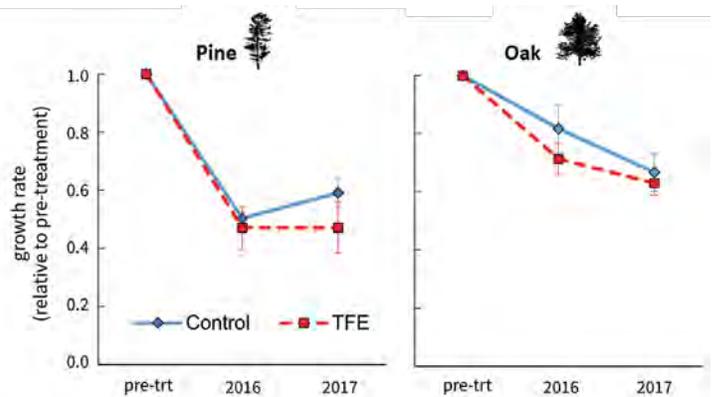


**Figure 3.** Sapflow ( $J_s$ ) in pines declines abruptly as soils dry beyond a water content of 14 percent, while the threshold for oaks was lower, at 10 percent.

The results indicate that both species reduced their growth significantly in 2016, but that growth reduction was more than twice as great for pines (**Fig. 4**). In 2017, pine trees started to show signs of recovery; however, the oaks continued to show further growth reductions and appeared to recover much more slowly.

These results suggest that red oak’s ecological strategy may be well-suited to surviving moderate droughts yet may make this species more vulnerable to extreme drought due to its inability to protect tissues from extensive damage.

The more conservative strategy of white pine may make it less competitive under moderate droughts—especially if they are repeated or prolonged—while conferring advantages for survival in severe droughts.



**Figure 4.** Wood growth (basal area increment in the first two treatment years relative to the last 5 years prior to the start of treatment) was reduced severely during the 2016 drought in both control and treatment pines. Growth reductions in oak were smaller in the year of the drought, but oaks compensated in 2017 following the drought (2016). Throughfall exclusion (TFE) represents data from the TFE plots.



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## WANT TO STAY INSPIRED?

NH Agricultural Experiment Station scientists are always working to address locally inspired challenges and improve the lives and livelihoods of Granite Staters through research and innovation. Sign up to receive the Station Science newsletter and be the first to learn about breakthroughs that make New Hampshire's food systems and natural resources more resilient and accessible for our state, region and beyond.

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# ENHANCING THE CHARACTERIZATION OF FOREST COMMUNITY COMPOSITION, STRUCTURE, AND HEALTH USING UNPILOTED AERIAL SYSTEMS

**B.T. FRASER AND R.G. CONGALTON**

**N**ew Hampshire has the second-highest proportion of land in forest in the U.S. (behind only Maine), with approximately 80 percent (4.68 million acres) in forest cover, according to the U.S. Forest Service. Cost-effective ways to assess the health and composition of the state's significant forestland are necessary for supporting long-term management and economic needs. However, traditional forest inventorying methods are resource intensive and may not support a full understanding of dynamic disturbances, such as climate change or invasive forest pests, pathogens and plants. This research considers whether new technologies such as unpiloted aerial systems (UAS) can help overcome the limitations of traditional assessment methods and provide more informative characterizations of northeastern forests.

## KEY TAKEAWAYS

Using scientifically developed best management practices, unpiloted aerial systems (UAS) can serve as a lower-cost, effective tool for supplementing field-based methods to characterize the forest.

UAS imagery can be used to measure individual tree health, as well as the growth of invasive species, increasing accuracy by 14.9 percent compared to traditional satellite imagery.

Combining UAS-captured forest imagery and digital photogrammetry can create more informative three-dimensional maps of forest composition.

## Traditional forest mapping

Local scale forest management necessitates both timely and accurate information. Data describing the species composition, forest structure and tree health are critical for meeting future natural resource demands. The conventional practice for acquiring forest data—continuously measuring forest inventory plots—may not capture the detailed characteristics necessary to support accurate and complete management decisions. Emerging technologies, such as UAS, have the potential to enhance traditional forest inventories by providing more informed assessments of rare community characteristics, dynamic disturbances or between-plot variability.

Remotely sensed data—including aerial and satellite imagery—have been a standard feature in forest management for over 50 years. However, they have often been limited to serving as a basic source of a birds-eye (synoptic) perspective due to their limited collection intervals or insufficient spatial resolution. UAS technology is leading to major innovations in remote sensing data availability and capability.

## Using UAS in forest mapping

For an investment as little as \$1,000, a highly capable UAS can be purchased and deployed to capture data at scales finer than the individual tree or plant. The research conducted in the UNH Basic and Applied Spatial Analysis Lab has focused on combining the capabilities of rapidly developing hardware with conventional practices in remote sensing to maximize their effectiveness. Research has been conducted to use digital imagery collected from UAS to analyze forest composition, structure, health and the growth of invasive species communities.

Each UAS flight begins with a site assessment and flight plan. Each mission is carried out via an automated mission planner (**Figs. 1** and **2**) to ensure the safety of the aircraft and the precision of the collected imagery. Depending on the information required, images are collected using either natural color or near infrared (NIR) sensors.

Including NIR light (**Fig. 3**) enables measuring individual tree health because healthy vegetation reflects high amounts of NIR light while unhealthy vegetation reflects much less. After collection, the imagery is processed using a combination of computer vision and digital image processing software to generate both 2D and 3D models. This workflow is often called digital photogrammetry, or Structure-



**Figure 1.** Postdoctoral scientist Ben Fraser uses a pre-programmed UAS mission midflight. The small quadcopter UAS is programmed to capture imagery for an assessment of invasive species population growth over time in Durham, NH.



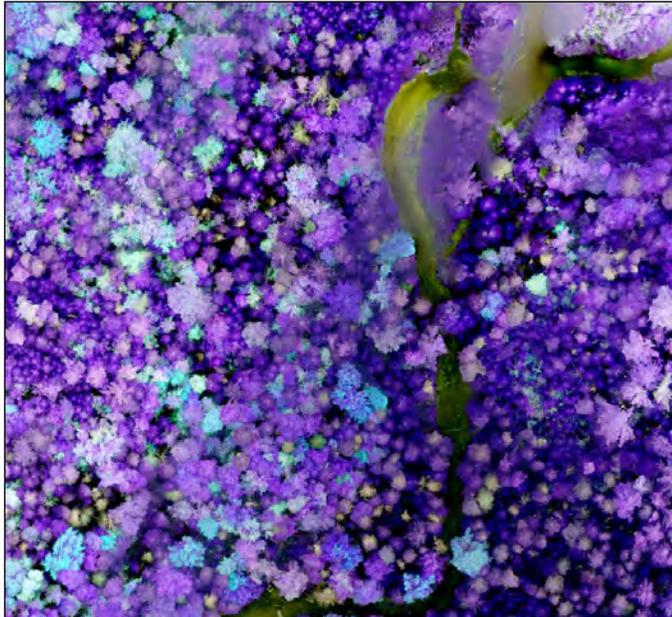
**Figure 2.** Ground control station during a routine flight at UNH-managed woodlands. The laptop serves as a communication and control element for a SenseFly eBee+ UAS. This picture is taken midflight, as demonstrated by the purple flight lines and aircraft located on the screen. The screen displays real-time flight diagnostics including distance to home, battery life, number of images captured, wind speed and time remaining in the mission.

from-Motion (SfM), and is highly effective at feature reconstruction using unordered imagery (**Fig. 4**).

## Pairing UAS and 3D reconstruction

The pairing of UAS and SfM is ideal because of the ability to capture and identify features across large image collections. In most instances, between 2,000 and 15,000 images are collected when mapping a single study area. The spatial data products from the SfM process can include ultra-high-resolution image composites (**Fig. 3**) or point clouds consisting of billions of points (**Figs. 4** and **5**). The combination of

geometric and spectral data supports a wide variety of measurements and observations.



**Figure 3.** A near-infrared (NIR) or ‘False Color Composite’ created using UAS imagery. This figure represents a small portion of a wider mapping area that contained approximately 10,000 images. The NIR imagery provides important characteristics for differentiating tree species and tree health.

Combining these spatial data with a machine-learning classification algorithm resulted in a higher overall accuracy for mapping species composition of between 4 percent and 16 percent when compared with results from traditional airborne imagery. During the assessment of forest structure, the UAS data generated a highly efficient estimate of individual tree diameter at breast height, stand basal area, tree density and stand density.

Using a combination of sensors, analysis of the UAS data produced a 14.9 percent higher overall accuracy than satellite imagery in detecting individual tree health. This assessment of tree health has since encouraged an investigation of more advanced sensors for detecting American beech (*Fagus grandifolia*) bark

disease. More broadly, these assessments have led to developing an aspirational holistic approach for forest monitoring, with other recent and ongoing research focusing on outlining best management practices in UAS flight planning and data processing for practitioners in the state and region.



**Figure 4.** The University of New Hampshire wildcat statue reconstructed using cellphone imagery and a Structure-from-Motion workflow. This 3D model is part of an introductory tutorial used for teaching computer vision fundamentals.



**Figure 5.** A photogrammetric point cloud and crown delineation generated using an individual tree detection algorithm (white). A combination of these structural data and spectral (color) data are used to evaluate species composition and individual tree biometrics.



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An aerial photograph of a forest edge on the left, transitioning into a topographic map of the same area on the right. The forest is shown in various shades of green, while the topographic map uses a color gradient from green to red to represent elevation changes.

# EVALUATING EDGE INFLUENCE EFFECTS ON FOREST CANOPY COVER USING IMAGERY FROM UNPILOTED AERIAL SYSTEMS

H. GRYBAS AND R.G. CONGALTON

**A**n outcome of continued urban growth in New England is the fragmentation of landscapes, which has led to increasing challenges in sustaining local biodiversity and ecosystem services. From 1983–2007, forested land was cleared in New Hampshire at an average annual rate of 3,000 acres, according to the U.S. Forest Service. Development across the Granite State has created challenges and questions around biodiversity and ecosystem changes at forest edges. This research used rapidly emerging unpiloted aerial system (UAS) technologies to estimate foliage cover and then characterize and measure changes in forest structure near forested edges. Improved methods for collecting and using UAS data are important for cost-effective, adaptable land management practices.

## KEY TAKEAWAYS

Unpiloted aerial system (UAS) technology effectively measures forested land edges frequently and consistently and at capturing greater land areas.

When comparing UAS data with imagery data collected at ground level, information from UAS accurately characterized tree canopy cover at forest edges.

UAS imagery and ground data detected edge effects and show a pattern of forest cover decreasing within 45-50 meters of the edge, followed by an increase.

## Measuring edge influences

When forest areas are removed, what remains is exposed to edge influences, which affect abiotic and biotic processes at the forests' edge. This can lead to significant ecological changes—more light availability, temperature variability and wind—as well as changes in forest structure (Fig. 1). As a result, plants and animals that once existed in a large patch of forest may not thrive or survive in smaller patches with new edges, while invasive species can enter.

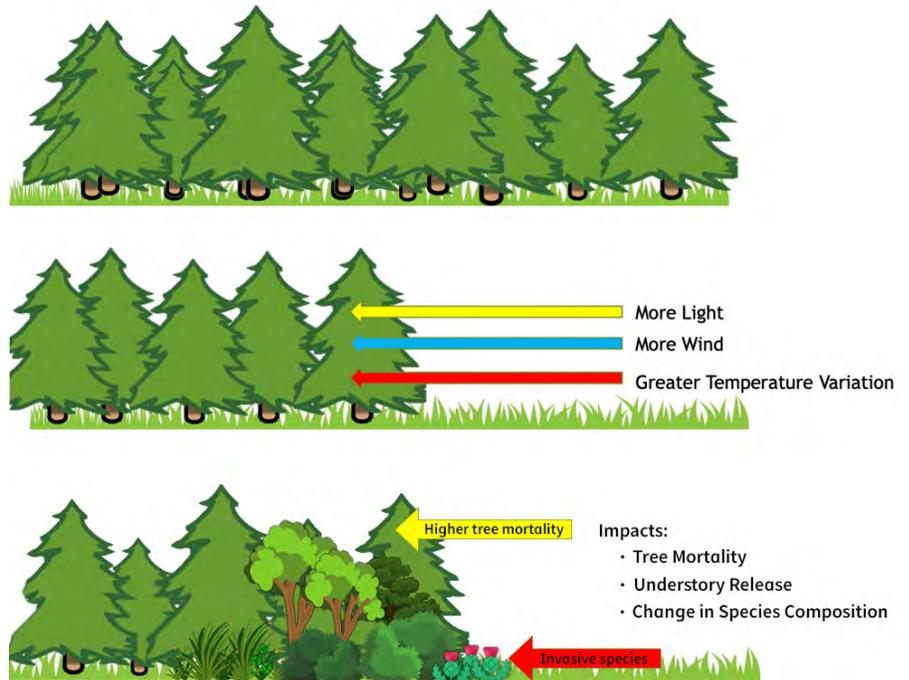
Characterizing and measuring the extent of change at forest edges is important for making land management decisions, especially in the face of climate change. However, making these assessments can be difficult due to the large number of factors that can affect conditions at forest edges. Previously, edge analysis of forested land was conducted using transects measured in the field. This study assessed the potential of imagery acquired from UAS to accomplish the same goal.

## Using UAS in forest edge measurements

Imagery collected using UAS has the potential to detect and measure the forest's response at the edge quickly and repeatedly, thus allowing a larger amount of area to be covered with less work. This study was an initial test of using UAS imagery to detect changes in foliage cover—a component of forest structure known to exhibit changes caused by edge influences—across forest edges in New England.

The study was conducted on Blue Hills Foundation conservation lands of nearly 7,500 acres in southeastern New Hampshire. The area represents a natural, highly mixed, transition hardwood-hemlock-white pine forest community.

UAS imagery was obtained of the study area on July 1, 2020, using an AgEagle (formerly senseFly) eBee X fixed-wing aircraft with an Aeria X digital single-lens reflex camera capturing high spatial resolution (24 megapixel) imagery in natural color (RGB). The imagery was collected 100 meters above the tree canopy, with 1,299 images collected in all.

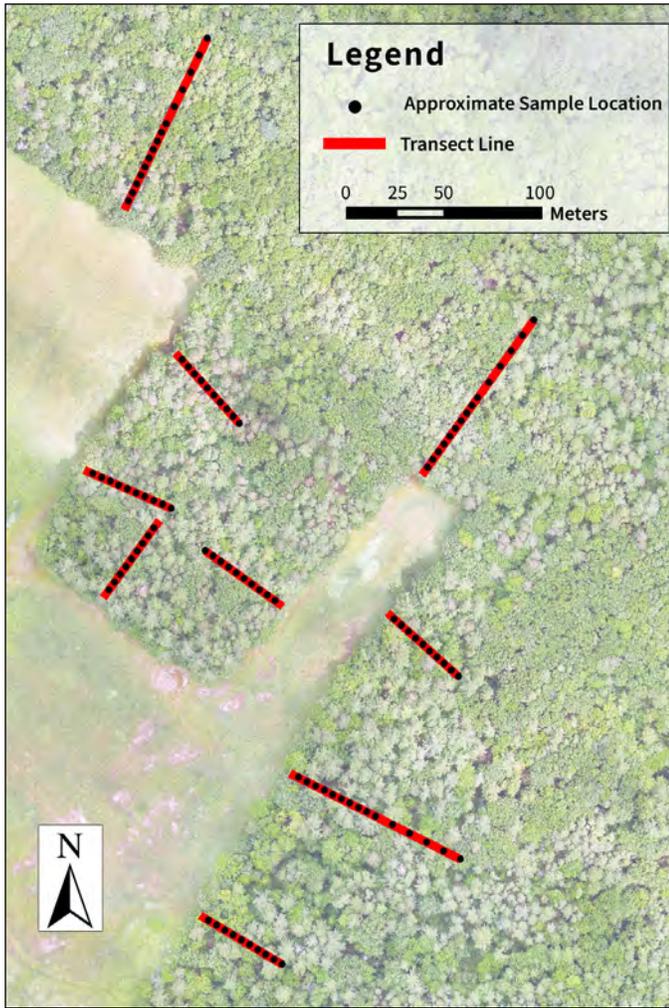


**Figure 1.** Progression that occurs when an edge is created where forest area is removed. Initially, there is more light and wind and a greater variation in temperature. These added variables can result in tree mortality, understory release and changes in species composition, including the addition of invasive plants.

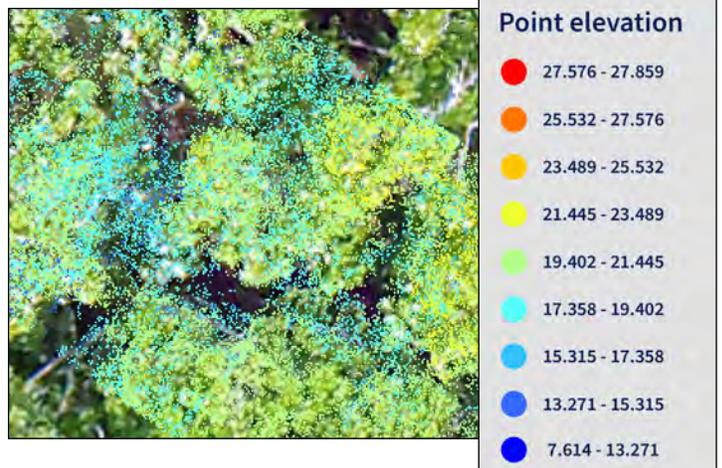
The imagery was processed using the Agisoft Metashape professional software to produce a 3D point cloud and an orthorectified mosaic. Changes in canopy cover with increasing distance from the forest edge were measured on the ground using digital cover photography and from imagery-based maps of canopy gaps produced from UAS data (Fig. 2).

The imagery-based canopy gap products were significantly similar to ground estimates for canopy cover ( $p$ -value > 0.05) than the photogrammetric point clouds, but still suffered overestimation (root-mean-square error of 0.088) due to the inability to detect small canopy openings (Fig. 3). Both the ground and UAS data were able to detect a decrease in canopy cover from between 45–50 meters from the edge, followed by an increase to 100 m.

The UAS data offered the advantage of a greater sampling intensity, allowing researchers to better detect a significant edge effect of minimal magnitude in the presence of heavy variability.



**Figure 2.** The estimated location of transects (red lines) and sample points (black dots) along each transect as measured on the ground. Locations for transects were based on GPS position beginning at the edge and following an azimuth bearing of the transect. Sample locations were systematically placed along the transect line, starting at 5 meters and extending to either 50 or 100 meters.



**Figure 3.** A comparison between the digital cover photos taken from the ground looking up (top image) and the 2.5 cm orthomosaic (center) and the photogrammetric point cloud (bottom) taken of a sample location.



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# MAKING THE BEST USE OF EMERGING REMOTE SENSING TECHNOLOGIES

M. DUCEY

Artist rendering showing a fully deployed NISAR satellite.

Source: NASA/JPL-Caltech

Upcoming spaceborne synthetic-aperture radar (SAR) missions—like the NASA-ISRO Synthetic Aperture Radar (NISAR) mission—promise frequent monitoring of the Earth’s surface, with high-resolution images regardless of cloud cover and other weather conditions that affect conventional satellite imagery. This emerging technology and data can offer an important new mapping tool of forest biomass and other attributes used in informing land management. However, common methods of analyzing SAR data may not lead to accurate estimates of forest characteristics. This study assessed why existing methods may lead to errors and points to ways that the new technology could be used for better forest biomass estimation.

## KEY TAKEAWAYS

Widely used statistical techniques that assess and interpret data from backscatter for measuring aboveground forest biomass can result in large errors.

Comparing model inversion and direct modeling approaches using forest biomass data from New England showed that the direct method predicted aboveground forest biomass more accurately.

Model inversion is useful for understanding how a particular synthetic-aperture radar (SAR) platform will perform, while direct modeling is best for mapping and predicting biomass.

## Estimating forest biomass from SAR data

The launch of the NISAR mission will provide freely available L-band SAR, which can penetrate clouds and provide observation of the Earth’s surface every 6 days. As a result, this mission has stimulated interest in the use of SAR for forest monitoring, including the assessment of aboveground biomass. To do so, however, scientists and practitioners must use statistical methods to interpret satellite-derived data in a way that provides useful information.

Statistical models are used to convert SAR backscatter—the pattern of radar signals that are emitted by the satellite and reflected from the tree canopy and other surfaces—into predictions of forest characteristics, such as biomass. SAR backscatter is driven by interactions with water in vegetation and other surfaces. Much of the work on the recovery of forest biomass from SAR involves the Simple Water Cloud Model (SWCM), developed by Evert Attema and Fawwaz Ulaby in the 1970s. Using the correct statistical approach is crucial to ensuring that the results—often presented as a map of forest biomass—are accurate.

All model-fitting methods rely on collecting an appropriate set of biomass data at known locations in the field, then extracting backscatter or other SAR variables for those locations from the satellite data. Much of the previous research on biomass mapping using SAR relies on a model inversion technique. In inversion, the parameters of a model such as the SWCM are chosen to give the best predictions of backscatter based on the observed biomass values. This gives an equation between backscatter and biomass. Then, new backscatter values are used to map and predict biomass using the fitted equation.

The inversion approach is intuitive, but it depends on a dubious statistical assumption—that the relationship between SAR backscatter data and biomass is perfectly or near-perfectly predictable. However, that is not the case. As such, the widely used inversion method may not provide the most accurate predictions of biomass.

An alternative is to predict biomass directly. By using the paired field and satellite data, parameters of the SWCM are chosen to give the best prediction of observed biomass. The resulting equation, which will be different from that obtained in the inversion approach, is then used to predict new biomass values from a map of observed backscatter.

## Testing the methods

This study compared the accuracy of aboveground biomass predictions using the inversion and direct methods with field data collected from 175 forest plots in New Hampshire and Maine. In the comparison, a technique called leave-one-out-cross-validation (jackknife) was used so that biomass at the plot being predicted was independent from the values used for model fitting. The results clearly show that the inversion technique provides poorer predictions; however, the direct approach for predicting biomass nearly eliminates bias and cuts root mean square error and mean absolute error nearly in half (**Table 1**).

A weakness of the direct approach is that its results do not shed light on the physical performance of a sensor design—one of the strengths of the inversion method. The two approaches are complementary and the purpose of an investigation should dictate which will be used. Where prediction of biomass is the main goal, the direct fitting technique is preferable.

**Table 1.** Prediction performance of the Simple Water Cloud Model for predicting aboveground tree biomass (Mg/ha) in forests in New Hampshire and Maine.

| <i>Fitting Mode</i> | <i>Bias, Mg/ha</i> | <i>Mean Absolute Error, Mg/ha</i> | <i>Root Mean Square Error, Mg/ha</i> |
|---------------------|--------------------|-----------------------------------|--------------------------------------|
| Inverted            | 43.2               | 124.5                             | 159.4                                |
| Direct prediction   | 0.1                | 65.1                              | 82.1                                 |



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## FOR FURTHER READING

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### Silvopasture: A Climate-friendly Alternative to Conventional Open Pasture Practices

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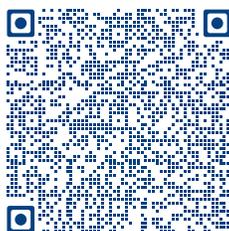
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