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Proceedings of the First Biennial Northern Hardwood Conference 2021: Bridging Science and Management for the Future



Virtual Conference
June 15-16, 2021

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Abstract

The first biennial Northern Hardwood Conference (NHC 2021) with the theme “Bridging Science and Management for the Future” took place virtually June 15–16, 2021. This inaugural meeting brought together scientists and managers working in the northern hardwood forests of eastern North America. Articles presented in this proceedings document the diverse subjects, cutting edge science, and state of the art practices exchanged among experts and across the subregions of the northern hardwood range. The topics include *People and the Forestry Profession*, *Regeneration and Biotic Interference*, *Stand Dynamics*, *Silviculture*, *Forest Products and Economics*, *Forest Ecology and Ecosystem Impacts from Forest Management*, *Forest Health*, and *Climate Change*. The proceedings include 52 extended abstracts, 7 papers, NHC Hosting Policy, and a list of articles (also presented at NHC 2021) published in a journal special issue.

KEY WORDS: ironwood, silviculture, management, forestry, wildlife, soils, climate change, forest health, ecology, Sugar maple, yellow birch, red oak, ash, research

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Proceedings of the First Biennial Northern Hardwood Conference 2021: Bridging Science and Management for the Future

An international conference to explore the history, current practices, and future options to sustain northern hardwood forests

Virtual Conference

June 15-16, 2021

Edited by:

Christel C. Kern, USDA Forest Service

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Foreword

Christel C. Kern and Gregory J. Edge¹

Dear Readers,

The Northern Hardwood Conference 2021 (NHC 2021) is the start of a biennial series of meetings dedicated to exploring the history, current practices, and future options to sustain North America's northern hardwood forests. The northern hardwood type occupies millions of acres of forest land in the eastern United States and Canada, representing one of the most economically important and ecologically diverse forests in eastern North America. Northern hardwood silviculture is diverse and complex and has been the focus of extensive research for over 80 years. Past conferences have shared and discussed northern hardwood topics, but at local or regional scales. A large conference has not been held in nearly 30 years and a rangewide conference has not been held to our knowledge. Today, practitioners continue to seek innovative management solutions to address the expanding challenges facing northern hardwoods, including serious threats such as invasive species, climate change, inadequate tree regeneration and shifts in composition, intense herbivory, and limited wood markets. Given the wide geographic range of the northern hardwood type, a rotating meeting much like the successful Central Hardwood Conference, seemed like the ideal approach to bring together both managers and researchers on a regular basis to share ideas.

The road to the NHC 2021 began far back in 2017 with development of a concept and a small team of partners. This grassroots effort grew into the technical, planning and biennial committees representing researchers and practitioners from across the northern hardwood range. A primary goal for the entire series is to improve the exchange of information and ideas among researchers and practitioners, and this was reflected in the NHC 2021 theme of Bridging Science and Management for the Future. The committees developed an incredible conference agenda, which was to be held in Green Bay, WI, in June 2020, but, along with the rest of the world, the COVID-19 pandemic changed everyone's plans. The committees worked hard once again to change to a virtual conference platform that was delivered on June 15–16, 2021. The conference platform included live and recorded presentations, virtual posters, and virtual field tours.

While this was not the original vision we had for this conference, we are thrilled with the results. With over 400 registrants from research and management fields, 4 provinces and 23 states represented, 90+ presenters, and 5000+ hours of viewing over 2 days, we think NHC 2021 was a successful start to the biennial series. The following proceedings represents the current science and state of the art management of northern hardwood forests that were delivered through over 75 presentations and posters. We thank all the committees, sponsors, technology support, presenters, and attendees for this inaugural meeting to kick off the Northern Hardwood Conference series! Our sincere gratitude to many authors, reviewers, editors, and the NRS publication production staff for playing various roles to put this publication together.

We look forward to future meetings across the range!

Christel Kern and Greg Edge

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PEOPLE AND THE FORESTRY PROFESSION

SUMMARY

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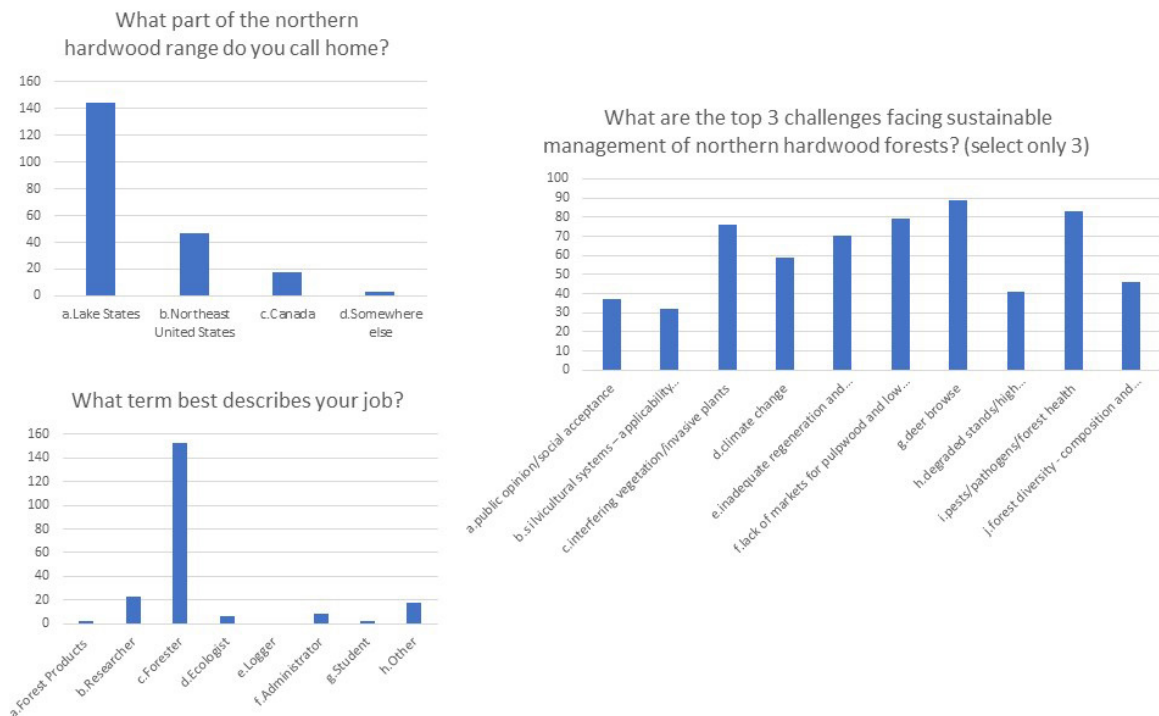


Figure 2.—Selected polling results from top-issue categories for northern hardwood forests as voted by the participants of the NHC 2021 Round Table day 1 (i.e., N = 212). The y-axis represents the number of votes.

At the conclusion of day 1, participants engaged in an icebreaker about polling questions. The results are presented in Figure 2. The last question presented participants with an abridged list of the 10 most common challenge categories and asked them to vote for the three most important. Two hundred and twelve participants voted. Interestingly, all challenge categories received votes and no topic received exceptionally higher votes than the rest. The top three categories were deer browse/herbivory (i.e., 14 percent), pest/pathogens/forest health (i.e., 13 percent), and lack of markets for pulpwood and low-quality material (i.e., 13 percent). Close in 4th and 5th place were the related categories of interfering vegetation/invasive plants and lack of regeneration and recruitment, with a combined vote total of 23 percent.

At the end of day 2, a panel of experts discussed the top challenge categories identified by participants. The panel included three managers and three researchers, representing different regions of the northern hardwood range. From the Lake States, Forrest Gibeault (Steigerwaldt Land Services) represented management and Mike Walters (Michigan State University) represented research. From the northeastern United States, Nancy Patch (Vermont Department of Forest, Parks, and Recreation) and Laura Kenefic (USDA Forest Service, Northern Research Station) represented management and research. From southeastern Canada, Gaetan Pelletier (Northern Hardwood Research Institute) represented management and Frédérik Doyon (University of Québec en Outaouais) represented research.

It was clear to panelists that the top challenges represented various threats facing the sustainable management of northern hardwood forests. Walters said, “Many of the top challenges prioritized by the participants are disturbances that challenge successful regeneration and forest sustainability.” He noted that important to this broad theme is the predictability of regeneration outcomes after treatment. Also, this broad theme was supported by ideas that emerged during panel discussion: collaborate (researchers and managers working together), monitor our work, manage adaptively, and keep management practices diverse.

A couple panelists noted a common topic in the conference presentations was that successful, and failed treatments were often preceded by onsite evidence that had been overlooked by the prescribing manager or researcher. Patch noted, “In this conference, the science community really pointed out the nuances of what we thought worked but isn’t actually working.” She noted practitioners can’t keep doing the same thing and nuances may indicate a new approach is needed. Kenefic said, “Sometimes we get caught up looking at the overstory when preparing harvest prescriptions and we are then surprised by the outcome,” and she noted that being more ecological and connected with the larger professional community results in becoming more knowledgeable in the success of a planned treatment. Overall, the profession needs to pay attention to the entire stand and landscape situation to be creative and ultimately develop prescriptions with greater potential success in challenging conditions.

Collaboration between researchers and practitioners was another takeaway. Pelletier mentioned that working across science and practice has been challenging for decades. He cited a 1994 article by Gordon Baskerville in the *Forestry Chronicle* as the epitome of this conundrum. Panelists highlighted moving forward as a profession will require training new professionals, as well as educating and engaging with groups beyond the profession. Patch noted that we need social acceptance to conduct silvicultural treatments and to get that acceptance we must work with groups that we haven’t traditionally worked with in the past.

All panelists agreed that using diverse approaches to management is important. Adaptive management will be key to developing a variety of successful silvicultural practices under a changing climate. Doyon noted that new assemblages and processes may result from climate change or climate-informed management. Management practices such as assisted migration will likely result in unknown responses to local and landscape factors, such as deer browse. He noted, “...past empirical evidence has traditionally informed silvicultural practices, but today this isn’t possible—everything is changing...” Understanding ecosystem function at a fine scale will be important to predicting stand and landscape outcomes under these changing conditions. Gibeault supported the idea of current silviculture being based on the past but from a different angle—past markets. Today, markets are emerging in forest carbon and the silvicultural tools to manage carbon—while also meeting other management objectives—are unclear. Gibeault said, “Ecosystem service markets are developing and will provide incentives or markets to do treatments in ways we haven’t in the past. This provides strong support to build the toolbox for silviculture.”

The concerns of the conference participants revolved around sustainability, notably the threat of numerous disturbances on natural tree regeneration. The panel suggested paying close attention to stand conditions and landscape context, working together across disciplines and with the public, and keeping silvicultural practices diverse. This strategy will keep management options open and reveal new approaches to sustainability in the years ahead. In the end, the round table discussions epitomized the theme of the conference, “Bridging science and management for the future.” We look forward to furthering these discussions at NHC 2023 in New Brunswick.

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Forest Management, the Menominee Tribe, Culture, and Traditional Knowledge

Adrian Miller¹

The history of Menominee Tribal Enterprises (MTE) is a fascinating and romantic story about our forest and how the Menominee people have successfully managed it for eons. Today, these management practices have resulted in an extraordinary, healthy, and productive emerald forest whose boundaries can be seen from space. The picture from space clearly shows more than a geographic boundary. It is silent testimony of a resilient culture that responsibly cared for their land, for the benefit of mankind and the planet itself. There is no story quite as powerful and compelling as MTE. That beautiful story is about the love of our land and how we managed the forest using the virtuous principals of love, honor, and respect.

Our tribal forest is as special as it is exemplary. Its philosophical, cultural, and spiritual framework speaks eloquently to the Native American Indian connection with Mother Earth. The old advertising maxim, “Sell the sizzle not the steak,” applies to MTE. We have an abundant amount of sizzle to sell that no one else has. It is ensconced in the sensitive way in which we balance our economic interest against our spiritual, ecological, and cultural interest. A wellspring of opportunities has surfaced here, especially from the rising number of consumers who are sensitive to the environmental issues related to living sustainably by respecting our Mother the Earth! Thus, our history of forest management will tell the world who we are and what we do; this is what MTE proudly stands for.

As an enrolled Menominee Indian and President of MTE, I am very proud of the vast continuous verdant forest we manage. This wonderful ecosystem has given life to the tribe for thousands of years. This emerald giant is more than a forest; it is our spiritual home. We treat it with love, honor, and respect. This precious forest is a sacred place of our cultural expression because it is a highly regarded part of our tribal identity and values. The Menominee Indians are the people of this “place.” And this place communicates to us that we have responsibilities to the rest of the natural world that transcend our own personal desires and wishes.

Through countless generations these principles stand at the forefront when we make decisions to manage “Akia”—meaning Menominee Land. The Menominee Forest stands as a cherished monument to the foresight of our tribal ancestors who vigilantly protected the sacred ground they inherited. Today, MTE strives to emulate our ancestor’s spiritual discipline. MTE in many ways embodies the culture, values, and spirituality of our forefathers. The values of Menominee culture lie deep in the soul of our forest. Native Americans, particularly the Menominee, are at the lead in articulating an indigenous epistemology that has moved beyond virtually anything in print or practice.

Furthermore, MTE has been built upon the understanding of the need to integrate advance science, technology, and business discipline into the organization, all within a cultural context. Our land ethic and commitment to sustainable forest management practices and principles uniquely sets the Menominee forestry apart from all other integrated forest management/wood products business, nationally and internationally. As native people, we need to promote a healthy tension as we compare scientific knowledge with our own cumulative wisdoms.

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Since 1854, MTE has harvested more than 2.5 billion board feet of lumber from our sacred land. We have completely cut standing timber over the entire reservation twice. Yet, today we have more than a half billion board feet additional standing timber than when we started. A drive through or fly over our forest would show the results of a forest that looked like it had never been cut.

Under the Menominee Tribal Enterprises Forest Management Plan 2012–2027, Menominee Tribal Enterprises has been charged with the responsibility of managing the forest, which is held in trust through the U.S. Secretary of the Interior for the benefit of the Menominee People. The Secretary of the Interior and the Menominee Tribe have a legal responsibility to manage the forest under sustained yield principles.

Hardwoods are an important component of management on Menominee lands. According to MTE log delivery data, during the past 15 years loggers delivered 147,447,747 board feet (BF) of sawlogs to the sawmill located in Neopit, WI. From that total, 104,336,257 BF were hardwood logs. The average annual hardwood log deliveries for the past 15 years are around 7 million BF per year. During a normal logging year such as 2007 to 2008, 15,367,440 BF were harvested from the Menominee forest. Of that total, 12,602,855 BF were hardwoods. Hardwoods accounted for 82 percent of the annual total cut. Due to the rapid decline in the logging force coupled with climate change, MTE annual hardwood log deliveries have declined more than 50 percent. The financial and social implication are serious as MTE relies heavily on its hardwood lumber sales to sustain the mill operations.

When it comes to ensuring forestry is practiced in an environmentally responsible, socially beneficial, and economical way, no one does it better than Menominee Tribal Enterprises. History has proved it. Continuous Forest Inventory (CFI) has certified it.

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Managing for Northern Hardwoods at the Landscape Scale: The Role of Family Forest Owner Preferences

Alexander C. Helman, Matthew C. Kelly, Mark D. Rouleau, and Yvette L. Dickinson¹

Abstract.—Managing northern hardwood forests using high frequency, low intensity silvicultural systems—such as single-tree selection—favors shade-tolerant species and can reduce tree species diversity. Management decisions among family forest owners (FFOs) can affect species and structural diversity within northern hardwood forests at regional scales. We surveyed FFOs in the western Upper Peninsula (WUP) of Michigan to understand likely future use of three silvicultural treatments: single-tree selection, shelterwood, and clearcut. Our results indicate FFOs were most likely to implement single-tree selection and least likely to implement clearcut within the next 10 years. According to logistic regression, prior use of a treatment and perceived financial benefits significantly increased the odds of likely use for all three treatments. Having received professional forestry assistance increased likely use of single-tree selection but decreased likely use of shelterwood. We discuss these results within the context of species diversity among northern hardwood forests throughout the region.

INTRODUCTION

Single-tree selection is often a preferred silvicultural system in northern hardwood forests among forest managers (Pond et al. 2014). However, recent research has shown that applying single-tree selection over multiple cutting cycles can result in conditions that strongly favor shade-tolerant sugar maple (*Acer saccharum*) over less shade-tolerant species, with implications for reduced tree species diversity (Hupperts et al. 2019). Misapplication of this system, which is associated with deviations from the Arbogast (1957) and other silvicultural guidelines, is also common (Pond et al. 2014). Combined, these factors motivate interest to explore alternative silvicultural methods when managing northern hardwood stands (Hupperts et al. 2020), with an objective of increasing species and structural diversity at landscape scales. Efforts to manage northern hardwoods across property lines are challenged by a mosaic of private and public forest owners, whose objectives, management history, and planning horizons can differ greatly (Bergman and Bliss 2004).

Family forest owners (FFOs) own a significant portion of the forested land in northern hardwood regions and their decisions affect the provision of ecosystem services at multiple scales (Aguilar and Kelly 2019). This study seeks to better understand the preferences and likely implementation of three silvicultural treatments among FFOs in the western Upper Peninsula (WUP) of Michigan. This research is linked to the Northern Hardwood Silvicultural Experiment to Enhance Diversity (NH-SEED) that was initiated in 2017 on the Ford Research Forest at Michigan Technological University (Webster et al. 2023, these proceedings). Thus, we only focused on the three main silvicultural methods used in NH-SEED: single-tree selection, shelterwood, and clearcut.

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Few studies have focused on FFOs familiarity with and likely future use of specific silvicultural methods. Specifically, understanding WUP FFOs willingness to implement treatments other than single-tree selection in northern hardwood stands will illuminate the potential for increasing structural diversity across the region. The results of this study will also inform efforts to coordinate ecosystem management across ownerships, such as landowner cooperatives. In that regard, information about FFO treatment preferences can help forestry professionals plan treatments on industrial and public forest land that consider the likely treatments applied to family forests in the region.

We hypothesized that expected outcomes regarding financial benefits, aesthetics, and wildlife habitat would affect FFOs' willingness to use each method. Additionally, we hypothesized that owner demographics and the characteristics of their property would affect implementation of each treatment.

METHODS

Using tax data, a simple random sample of 1,600 FFOs who owned at least 20 acres or more of contiguous forest land in the WUP were selected to be included in the mailing list. The survey booklet included questions to measure respondents' familiarity with the harvest treatments, their past use of treatments, and the likelihood that they would implement each treatment within the next 10 years. Respondents were shown images of each treatment from the NH-SEED study site and provided a short description of each treatment. The survey received a response rate of 31 percent. Descriptive statistics and logistic regression models with odds ratios were used to estimate the effects of explanatory variables on the probability that a landowner would implement a treatment in the next 10 years.

RESULTS AND DISCUSSION

Respondents reported being moderately or extremely familiar with terminology in the following order: clearcut (87 percent), single-tree selection (57 percent), and shelterwood (28 percent). About half of respondents reported previously implementing single-tree selection (52 percent) and of those respondents, 87 percent were either satisfied or very satisfied with the outcomes. Of the 11 percent of respondents who implemented a clearcut, 73 percent indicated that they were either satisfied or very satisfied with the outcome. When asked which of the three treatments they were most likely to implement in the next 10 years, a majority (66 percent) indicated they were most likely to use single-tree selection, while nearly 19 percent of respondents selected shelterwood and less than 4 percent selected clearcut.

According to the regression analysis, three variables were significant at the $\alpha = 0.10$ level for all three treatments: having conducted a commercial harvest previously, having experience with a given treatment, and the importance of financial factors when considering likely use of a treatment. Odds ratios for landowners who had previously conducted a commercial harvest were less than one for all three models, indicating that the odds of using a treatment again were less than the odds of not using a treatment.

Previous use of a given treatment resulted in an odds ratio greater than one, indicating likely future use of that treatment. Financial factors proved to be a strong motivator with greater-than-one odds ratios across all treatments. Unlike shelterwood and single-tree selection, which had positive significant results for landowners concerned about wildlife habitat, there were no positive significant results for the clearcut method other than financial factors.

Table 1.—Harvest method most likely to be implemented by respondents (n = 455)

Method	% of Respondents
Clearcut	4%
Shelterwood	19%
Single-tree selection	67%
None	11%

Single-tree selection was clearly the preferred method among FFOs in this study (Table 1). However, our results show that there is interest among landowners in implementing more intensive methods, especially when financial benefits were considered. Aesthetic concerns did not result in significantly negative results for the likelihood of FFOs to implement clearcut or shelterwood, which also means there is an opening for forestry professionals to introduce these methods in their work with landowners.

Past research has shown that landowners who receive assistance are more likely to engage in forest management activities (Kilgore et al. 2015). In this study, landowners with management plans written by a professional forester were 2.6 times more likely to use single-tree selection. This suggests that future use of a single-tree selection system among FFOs may be influenced by prescriptions written by consulting foresters which, in turn, reflect a regional norm regarding the use of a selection system to manage northern hardwoods.

The Upper Peninsula has some history with cooperative ecosystem management (Beyer et al. 1997) that could prove relevant given the results of this study. Cooperative management of forests across land ownership types and boundaries would give FFOs in the WUP greater access to professional expertise and management options. Implementing alternatives to single-tree selection on a landscape scale would prove less challenging with a cooperative agreement in place. The results of this study could help inform such efforts and guide management decisions across ownership types.

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Northern Hardwoods through the Eyes of Practitioners: Case Studies on the Great Lakes Silviculture Library

Eli Sagor and Marcella A. Windmuller-Campione¹

Every time natural resource managers design and apply a treatment to a forest stand, then observe or monitor outcomes of that treatment, they learn about how a system responds based on numerous factors. Lessons from silvicultural treatments implemented within an agency or company can provide a wealth of knowledge within it, there are relatively few opportunities for practitioners to share those lessons across administrative boundaries. We created the Great Lakes Silviculture Library in 2015 to provide a platform for practitioners to share these lessons more broadly.

The Great Lakes Silviculture Library is a free, open-access library of real-world forest management case studies, hosted by the University of Minnesota's Cloquet Forestry Center (Fig. 1). Most case studies are published by professional resource managers from the states of Minnesota, Wisconsin, and Michigan, United States, and the Canadian Province of Ontario. Reviewing case studies gives users a valuable insight into practical questions, issues, and solutions faced by the people making management decisions across Lake States forests.

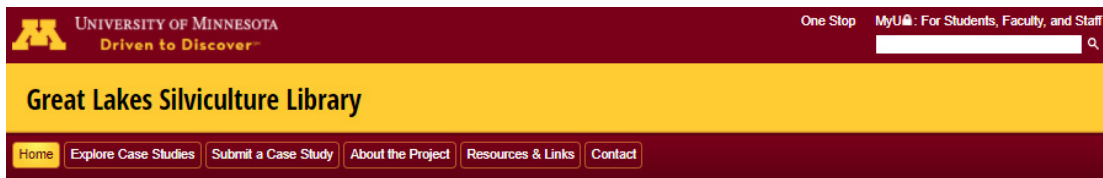
Case studies are generally the equivalent of three to five standard pages of written text, following a flexible content template provided by library editors. Most case studies are authored by resource managers. The library is online at <https://silvlib.cfans.umn.edu>.

We reviewed the content of published Great Lakes Silviculture Library case studies addressing northern hardwoods stands. Our objective was to characterize and describe the content of these northern hardwoods case studies, with a focus on the following questions:

- What questions are natural resource managers asking?
- What problems are they facing?
- What silvicultural systems are they applying?
- What lessons and themes emerge from their work?
- To what extent can case study data serve as the foundation for useful research into practical silviculture issues?

As of June 2021, 123 case studies were published in the library. To identify case studies pertaining to northern hardwoods, we used the following inclusion criteria: (1) categorized by the authors and editor as northern hardwoods cover type; (2) content focused on species most commonly considered northern hardwood: paper birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*), basswood (*Tilia americana*), sugar maple (*Acer saccharum*), beech (*Fagus* spp.), northern red oak (*Quercus rubra*); and (3) focus on aspen (*Populus* spp.), white spruce (*Picea glauca*), hemlock (*Tsuga* spp.), or other species but only in combination with management designed to promote the northern hardwood species in the second group.

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This site is designed to help forest managers from Michigan, Minnesota, Ontario, and Wisconsin exchange silviculture prescriptions, including the outcomes of actual on-the-ground management activities. The cases linked below are real, on-the-ground stories submitted by Lakes States natural resource managers.

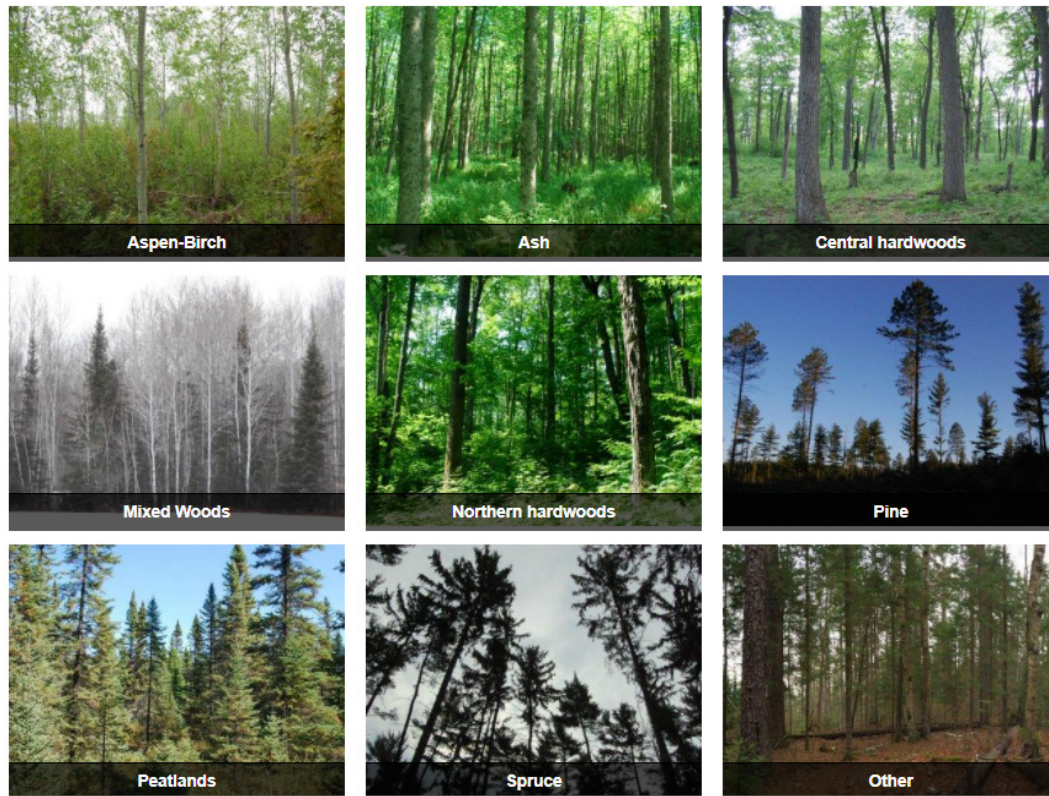


Figure 1.—The Great Lakes Silviculture Library homepage at the time of the 2021 Northern Hardwoods Conference.

We used the following exclusion criteria: (1) case studies describing pure mixed-oak management, no management for “core” northern hardwoods species; and (2) focus exclusively on white oak (*Quercus alba*) or other peripheral species.

Applying these criteria, we identified 28 case studies as pertaining to northern hardwoods.

BASIC DESCRIPTIVE STATISTICS

Northern hardwoods case studies are nearly all from public ownerships and are mostly from Minnesota. Of 28 case studies, 17 are from stands in Minnesota, 9 are from Wisconsin, and 2 are from Ontario. Ownerships included 11 state owned properties, 9 county owned properties, 3 tribal or federal/crown owned properties, and 2 private properties.

SILVICULTURAL GOALS AND SYSTEMS APPLIED

Silvicultural goals were included for 26 of 28 case studies. Nineteen case studies focused on regeneration objectives, four on intermediate treatments such as thinning or timber stand improvement, two on sanitation or salvage, and one on browse protection. Two case studies were excluded from this analysis because they involved only enrichment plantings in an assisted migration study.

Case studies applied a variety of silvicultural systems including shelterwood (9), variable density thinning (3), single-tree selection (3), group selection (3), and the seed-tree system (2). The other eight case studies focused on site preparation, species thinning, sanitation, or browse protection treatments and did not include a regeneration harvest.

THEMES AND EXAMPLES

Case studies revealed a high level of creativity and practical innovation. While admittedly subjective, interesting examples include:

- Throwing out the rulebook, relying on forester judgement in a declining stand: 33 years of northern hardwood management, Ashland County, WI²
- A creative use of shelterwood to regenerate black cherry on Crown lands in Ontario³
- Conifer strongholds: Assisted migration enrichment plantings, by The Nature Conservancy and Superior National Forest⁴
- Variable density thinning over multiple cutting cycles to maintain a multi-aged northern hardwood stand in Aitkin County, MN⁵

The following themes were common in the northern hardwoods case studies:

- Diversifying stands to increase resilience
- Regenerating northern hardwood species including paper birch, yellow birch, basswood, sugar maple, beech, northern red oak
- Simplifying complex silvicultural systems
- Forest health issues including deer browse, oak wilt, and sedge competition

Although all case studies were published in 2015 or later, climate adaptation was not mentioned as a common focus. Several case studies involved practitioners experimenting with making complex single-tree selection or variable-density thinning prescriptions simpler, more practical, and easier to apply operationally.

VALUE AND LIMITS OF CASE STUDY DATA

Case study data have value as way to share practitioner knowledge, priorities, and management issues. These data provide examples of how natural resource managers are using different silvicultural techniques to meet management goals and objectives. The goal of the Silvicultural Library is not to replace peer-reviewed products. What it can and does do is open opportunities for communication that may lead to deeper investigation through replicated studies with statistical analysis. Case studies also have value as a source of ideas or solutions from across administrative boundaries (Moser et al. 2022).

The case studies submitted to the Silviculture library do not reflect a random sample. Thus, case studies likely do not reflect all questions or lessons learned by practitioners. The number

² <https://silvlib.cfans.umn.edu/content/33-years-northern-hardwood-management-ashland-county>

³ <https://silvlib.cfans.umn.edu/content/shelterwood-regenerate-black-cherry-crown-ontario>

⁴ <https://silvlib.cfans.umn.edu/content/conifer-strongholds-changing-northwoods-landscape-crooked-lake-usfs>

⁵ <https://silvlib.cfans.umn.edu/content/multi-aged-northern-hardwood-forest-aitkin-county>

of case studies is limited but growing. As the data pool continues to grow, more similarities and differences in issues across regions, sites, and treatments can be explored. A final limitation may be the amount of data and the type of data collected; the data collected are generally part of a management organization's internal inventory and monitoring protocols, which vary across organizations and are designed to answer questions different from those of interest to library users.

CONCLUSIONS

Twenty-eight of 123 case studies published on the Great Lakes Silviculture Library describe real-world northern hardwoods silviculture treatments. Most describe work on public lands. These case studies include a diverse mix of silvicultural treatments with a variety of objectives that include increasing stand diversity, reducing forest health threats, and regenerating desired species.

Platforms like the Silviculture Library give foresters a voice and can inform future applied research. We're always looking for case study submissions.

The slides accompanying this presentation are available at <http://z.umn.edu/nhcSL>.

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Science-Management Collaboration is Essential to Address Current and Future Forestry Challenges

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Abstract.—Accelerating changes due to climate, invasive insects, plants, and diseases; and social values in northern hardwood forests make understanding and predicting impacts of natural and human variables ever more complex. Yet policy-makers are disinvesting in forestry research. We believe that science-management collaboration can help bridge the resulting gap. We give examples of advances in sustainable forestry from such collaboration and identify common elements of successful collaborations. Then we propose a new, three-tiered approach to science-management collaboration to reverse the trend away from forest science. Can such collaborations help us keep pace with forest change and develop management strategies to sustain forest values and benefits in the face of these changes?

INTRODUCTION

Northern hardwood forests are facing unprecedented changes at an accelerating pace while scientific capacity in forest ecology and forest management is diminishing. Can science-management collaboration help to address these changes? Integrating observations and insights from forest managers and results from deliberative adaptive management with traditional forestry research has the potential to bridge emerging scientific gaps. This cohesive approach facilitates prioritization of scarce research resources to the most essential problems. Our purpose in this paper is to illustrate the historical value and success of science-management collaboration and to outline models of collaborative adaptive management and traditional research suited to the present situation.

MANY CHANGES, ACCELERATING PACE

The stressors facing northern hardwood forests are many and interacting. Climate change is moving climate envelopes that favor individual species away from their current locations (Peters et al. 2020). The pace of these changes is anticipated to increase with increasing atmospheric carbon levels, and changes will persist even if we succeed in stabilizing or reducing emissions of greenhouse gasses. What were once called natural disturbances, such as windstorms and flooding, are more frequent and intense (Hayhoe et al. 2018). Yet eastern forests, particularly in the mid-Atlantic region, have insufficient advance regeneration to replace canopy trees in about 50 percent of areas surveyed (Miller and McGill 2019, Vickers et al. 2019). Atmospheric carbon has directly increased plant growth and fecundity (Norby et al. 2005). Resulting increases in maximum density shown in aspen may potentially render existing density management tools obsolete (Kubiske et al. 2019). Anthropogenic sources increased both nitrate and sulfate availability to forests in the twentieth century, resulting in nitrogen saturation in some forests (Aber 2002), but potentially benefitting species such as black cherry and tulip poplar elsewhere (Thomas et al. 2010, Canham and Murphy 2016). These inputs are now sharply declining and new changes are observed as

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ecosystems re-equilibrate (Royo et al. 2021). Invasive plants, insects, and diseases are other factors forcing change in forest ecosystem processes and values. Moreover, novel and changing climate conditions may affect invasive insect, disease and plant composition, density, competitive interactions, distribution, and management strategy effectiveness (Hellman et al. 2008). Interactions among these factors and with social changes such as changes in land use, increased recreation use, changing demand for species and types of wood products, changes in energy sources and infrastructure, and reduced hunting pressure will affect species and competitive interactions variably, further complicating the challenge of sustainable forest management in northern hardwood forests.

Keeping pace with these changes and managing these forests responsibly demands that all of us—scientists and managers alike—share and organize the observations regarding tree growth, health, seed production, seedling competitiveness and other factors to maximize shared insights and awareness.

In the Allegheny Plateau ecoregion, we have faced change with the help of close science-management collaboration for over 50 years (Stout and Brose 2014, Stout 2019). Our experience has shown that when scientists and managers interact on a regular basis in the context of careful observations of the forest, changes are detected and patterns emerge that help shape hypotheses about their causes and appropriate management strategies for addressing them.

SOCIAL INVESTMENT IN FOREST SCIENCE IS AT AN ALL TIME LOW AND DECREASING

Nearly 20 years ago, the National Research Council conducted a review of U.S. forestry research capacity and found that “Forestry research capacity is at a crossroads, if not a precipice” (National Research Council 2002). Wheeler et al. (2015) reported that late twentieth century changes in forest landownership from forest industry to timber investment management organizations (TIMOs) and real estate investment trusts (REITs) were associated with reduced financial and in-kind investment in forestry research. From 2016–2020, the Forest Inventory and Analysis (FIA) budget within USDA Forest Service Research and Development (R&D) held steady; thus, the 12 percent decrease in overall R&D funding resulted in a 16 percent decrease in non-FIA R&D funding (USDA Forest Service 2020). D’Amato et al. (2018) reported declining McEntire-Stennis and USDA Forest Service investment in university research, along with loss of forestry-specific faculty positions through disciplinary consolidation.

McGinley et al. (2019) compared 2016 data about university and agency investment in forest science to the data collected by the National Research Council in 2002. They found a 12 percent decline in the number of forest scientists over that 14-year period. Inflation during the same period neutralized the small absolute dollar increase in investment in forest science. The authors summarized their results: “The data indicated that the nation’s forest research capacity continues to erode, leading to declines in research development and innovation, and putting at increasing risk the future health and productivity of America’s forests.” In short, as the rapid pace of ecological changes creates management uncertainties, forest research capacity has diminished. We argue that science-management cooperation has enhanced the science basis for forest management in the past and can be an important way to support sustainable forest management now and in the future. Active collaboration that encourages managers to help set priorities, implement adaptive trials on their own properties, choose which questions merit investment in designed studies, and share observations of change on a regular basis may also inspire increased investment in the designed research process. First, we look at two long-established examples of science-management cooperation highlighting specific advances in science that fed back into improved management.

SCIENCE-MANAGEMENT COLLABORATION CAN HELP

Michigan Partnership in Ecosystems Research and Management (PERM)

Walters et al. (2020) describe a science-management collaboration in Michigan: The Partnership for Ecosystem Research and Management (PERM). The primary partners are Michigan State University (MSU) and the Michigan Department of Natural Resources (MDNR). After about 20 years of successful collaboration, scientists and managers alike were concerned that, “the historically dominant silvicultural system, single-tree/small group selection (i.e., selection silviculture), is not producing well stocked, species-diverse tree sapling recruits.” Together, they hypothesized that the interaction of selection silviculture with browsing by white-tailed deer (*Odocoileus virginianus*) could be among the most important factors contributing to this result. Solving the problem would require balancing economic, recreational, and ecological factors to “ensure sustainable, resilient forests alongside socially acceptable deer populations.” They thought that the problem was too urgent for traditional small-scale studies that did not account for geographic variation in site conditions, deer browsing pressure and other factors across which the results would have to be applied. They believed that local adaptation of results would be facilitated by this approach as managers throughout the state would have examples of alternative silviculture in their back yard.

At MSU forestry scientists and wildlife biologists conducted a comprehensive literature review of northern hardwood forest responses to alternative silvicultural treatments and interactions with deer. This created a common language and framework as scientists and managers designed practical alternatives to be tested on the scale that partners believed necessary. Ultimately, they chose four silvicultural systems and two understory treatments to test on a network of study sites distributed across three different Michigan ecoregions, on public and industry land. The overstory treatments were single-tree/small-group selection (the current dominant system), large-group/patch cutting, shelterwood, and seed tree. The understory treatments were herbicide-scarification and leaving tops to deter deer browsing. This study has now been installed on 140 sites, supported by substantial financial and in-kind support from MDNR and other interested partners.

Regular communication with partners at all levels has been and continues to be imperative. Meetings rotate around the state and allow for the exchange of observations with personnel at every administrative level, increasing the power of the experiment by drawing scientists’ attention to details and associations that field personnel will be the first to notice.

Pennsylvania’s SILVAH Community of Practice

The SILVAH² community of practice that originated in northwestern Pennsylvania in the late 1960s is another example (Stout 2019). Science-management collaboration among USDA Forest Service scientists and managers from state and federal agencies, forest industry, consultants, and nongovernmental organizations has been sustained by regular training sessions, field trips with manager and scientist input, and frequent research reviews. These interactions ensure a common language and framework for describing forest conditions. Research based on this collaboration informs management on hundreds of thousands of forested acres in Pennsylvania and beyond. SILVAH’s history includes many examples of important scientific breakthroughs that demonstrably benefited from manager input, such as the three offered here.

² Originally an acronym for Silviculture of Allegheny Hardwoods, SILVAH is a systematic approach to silvicultural prescription development based on inventory and analysis of stand data.

In the 1960s, managers and multiple case studies identified overabundant deer as a principal cause of widespread regeneration failures in the ecoregion. The U.S. Department of Agriculture (USDA) Forest Service team worked with managers on a study to test the effect of deer density on forest regeneration establishment, diversity, and growth (Horsley et al. 2003, Tilghman 1989). Study plots were multiple managed forest enclosures with each enclosure stocked with one to four live deer to achieve a range of white-tailed deer densities spanning the region's historic populations. Each enclosure started with the same proportion of its area in forage-producing conditions (10 percent early successional habitat). Investigators expected regeneration failures in the high deer density treatments (e.g., ≥ 40 deer per square mile) given the observed failures in managed forests on the landscape at those densities. After 5 years, regeneration was more abundant, albeit with low diversity, at the highest deer densities not anticipated. Conversation among scientists and forest and wildlife/game managers led to the hypothesis that forage in the study areas was greater than that available on the surrounding managed forests. There, managers intentionally withheld harvests until they could establish adequate advance regeneration resulting in approximately four percent of the landscape in clearcut, early successional habitat. Moreover, even when harvested, these areas were often fenced to mitigate overbrowsing, thereby eliminating them as a source of forage for deer. The results of these operational practices were lower proportions of good habitat, less accessible forage, and intensified deer impacts in the area's managed forests. This hypothesis was confirmed by a landscape-scale study made possible only by extensive management partner in-kind services (Royo et al. 2017).

In the late 1980s, managers and scientists became concerned about extensive dieback, mortality, and lack of regeneration in sugar maple (*Acer saccharum* Marshall). USDA Forest Service scientists organized a field trip to study the variation in condition of sugar maple trees and seedlings on the landscape, with sites suggested by managers. Managers showed that plateau-top positions in the unglaciated portion of the ecoregion were the sites with the most severe dieback and mortality, and that some of the healthiest trees occurred in glaciated areas. These observations became the basis of a northeast-wide study that confirmed the observations of the managers and tied the differences to soil calcium and magnesium levels (Horsley et al. 1999, Horsley et al. 2002, Long et al. 2009).

More recently, managers and scientists became aware of diminished establishment, growth, and survival of black cherry (*Prunus serotina* Ehrh.) seedlings. USDA Forest Service scientists reviewed the literature and contrasted results from current studies with those conducted decades earlier. They documented changes in precipitation patterns, reductions in nitrogen and sulfur deposition, apparent changes in virulence of fungal pathogens, increases in proportion of standing dead black cherry on several networks of forest health plots, decline of black cherry seed production, and more. Managers reported more abundant, healthier, and more persistent black cherry regeneration on sites with low proportions of cherry in the overstory compared with those with higher percentages of cherry, pointing to possible interactions with soil pathogens (Reinhart et al. 2005), and some suggested possible interactions between reduced nitrate and sulfate deposition and pathogens. Royo et al. (2021) summarize the status of this work, highlighting results that emerge from science-management collaboration. "Our review of the existing evidence suggests that altered nitrogen deposition dynamics and strengthened negative soil microbial feedback loops..., particularly given a warmer and wetter climate, represent promising avenues for future research."

In each of these cases, and others, results from research based on manager observations led to management change. More extensive use of fencing and more thoughtful planning about landscape forage availability have been used to increase diversity and success of regeneration harvests. Silviculture to favor sugar maple on the unglaciated Allegheny Plateau is focused on

lower landscape positions that have higher levels of calcium and magnesium. Managers are actively adapting their regeneration expectations and silviculture to favor other species on sites with high proportions of black cherry in the current overstory.

Recently, managers and scientists in the Allegheny Plateau region have taken a step towards more formal organization. The Allegheny Forest Health Collaborative (AFHC) was formed in 2017 with more than 40 member organizations, and its working groups are developing strategies to address forest health problems like invasive insects, diseases, and plants with early detection and rapid response, and to develop adaptive management guidelines across ownership boundaries for stands affected by the very factors we listed here (Hanson et al. 2020). The AFHC Research Working Group is engaged in conversations about a potential research cooperative.

In addition to SILVAH and PERM, for which we are able to point to specific scientific advances that come as a result of science-management cooperation, we point to three other examples of recent or existing science-management collaborations to inspire new and future collaborations.

Canadian Industrial Chair Research Grants

Until recently, the Natural Resources and Engineering Research Council of Canada supported a program called Industrial Chair Research Grants. This competitive grant program supported collaborations between Canadian universities and private and/or public sector partners leading to economic, social, or environmental benefits for Canada. The industrial or eligible public-sector organization made a financial commitment to partner financially with a leading scientist to conduct an intensive, sustained research program, matched by the government for successful applicants. Recently, for example, Steeve Côté of Laval University held an Industrial Chair Research Grant for two 5-year terms to understand the impact of moose (*Alces alces*) and white-tailed deer on forests on Anticosti Island. The research results enhanced understanding of ungulate browser-forest interactions far beyond the forests where they were conducted (e.g., Beguin et al. 2009, Cardinal et al. 2012), and were guided throughout by input from the forest industry based on their sustainable forest management needs for the island and beyond.

Research Cooperatives

Research cooperatives engage private, public, and academic organizations to finance and address shared research priorities. As we noted earlier, support for cooperatives diminished as forest land ownership passed from forest industry to REITs and TIMOs in the latter part of the 20th Century. The 50-year-old Forest Productivity Cooperative (FPC), based in the United States at North Carolina State University and Virginia Technical University, is one of the best known and most successful forestry research cooperatives. The FPC has 40 members and an annual budget at millions of dollars; private landowner members pay dues in proportion to the number of planted acres they own, while public agencies and nonlandowning stakeholders pay flat fees. Participating universities support some permanent positions for the Cooperative's work, but mainly the permanent staff of 15 is paid by stakeholder and member dues. The remaining dues support designed research studies. The landowning members choose which working groups (such as genetics or fertilization) receive their dues, and the scientists and managers on the working groups set the research agenda for each. The FPC hosts regular meetings and field tours to share results and observe conditions on experimental sites. There are several other working examples of this kind of cooperative around the country, most of a smaller scale, such as the Maine Cooperative Forestry Unit (Anderson and Ferguson 2020), the [Sierra Cascade Intensive Forest Management Research Coop](#), and the National Council for Air and Stream Improvement (NCASI).

Adaptive Management Cooperatives

The previous examples show science-management collaboration to support traditional, designed research. The best example we know of collaborative support for adaptive management is the partnership between The Nature Conservancy and the Washington-Jefferson National Forest to adaptively manage a large-scale prescribed fire program on their lands (Lorber et al. 2018). The most important difference between this model and the traditional cooperative model is that there are no designed studies. Rather, managers and scientists collaborated to define the desired future conditions to be achieved by a landscape-scale prescribed fire program, and the environmental and biotic factors that might influence achievement of the desired conditions. Then they designed a monitoring program to measure outcomes and influencing factors across a very broad landscape. Participating members collect data on assigned monitoring plots each year and financially support a staff that manages data collection, analysis, and storage. Communication among cooperative members is sustained through regular meetings and field visits. The staff also coordinates the data-based adaptive management cycle.

Common Attributes of these Science-Management Collaborations

There are compelling commonalities among these examples of productive science-management collaboration. Researchers and managers are critical to their success—researchers develop, implement, and tease out significant findings and implications for management strategies, while managers and field personnel are often the first to notice ecosystem changes or patterns that can be significant when viewed collaboratively through a broader lens. Both are needed to facilitate collaborative discussions and idea generation. In the face of disinvestment in forestry research, these collaborations offer a viable model for science-based collaboration to support adaptive management of northern hardwood forests.

MODELS OF INSTITUTIONAL SCIENCE-MANAGEMENT COLLABORATIVES

We believe that such collaboratives require several elements to succeed:

- Sustained institutional and financial commitment by management and science partners, their organizations, and their personnel, ensuring investment and ongoing participation
- Frequent two-way communication based on mutual respect, including site visits
- Development of a common framework and language for sharing observations tied to a strong, shared sense of place
- Purposeful inclusion of management priorities and informational needs when planning a research agenda

A Proposed Hybrid Model

The rapidly accelerating rate of change across regional scales in northern forests may require a hybrid of the Research Cooperative and Adaptive Management/Natural Experiment Cooperative models. Adaptive management or natural experiments³ can add to regional forestry knowledge bases in a flexible, possibly quicker, and coarse-grained way. Shared engagement in defining

³ A natural experiment is an empirical study in which individuals are exposed to the experimental and control conditions that are determined by nature or other factors outside the control of the investigators. The process governing the exposures arguably resembles random assignment (Wikipedia, accessed May 19, 2021).

problems and learning from the results of formal adaptive management or natural experiments can serve as a sieve through which the most critical hypotheses must pass to become the basis for the more robust and fine-grained results that come only from designed studies.

We see this as a basis for new, self-interested public/private investment in forest ecological and management research. The vision we have is that public management agencies, forest industry, and forest managing NGOs will form cooperatives with scientists willing to commit to conducting research according to priorities identified with managers. Such cooperatives will identify landscape-scale changes that require relatively immediate management responses, such as the widespread black cherry decline observed in the Allegheny Plateau ecoregion. Together, as the members of the Nature Conservancy/Washington-Jefferson National Forest cooperative have done, they will identify specific desired outcomes and determine the metrics needed to determine whether adaptive strategies are yielding desired outcomes. Some cooperative contributions (in-kind and financial) will be expended to monitor outcomes at the landscape level and analyze their correlation with biotic, environmental, and management factors. In the Allegheny Plateau case, this might mean monitoring at the landscape (rather than stand) level the composition, diversity, and growth rate of regeneration in stands managed according to adaptive guidelines in cherry-decline impacted stands. At the same time, the cooperative would identify a subset of questions of management relevance that merit a more rigorous designed-study approach and provide support to scientists to conduct such studies. In the Allegheny Plateau case, this might include formal tests of fertilization or fungicide application to increase survival and growth of seedlings. When resources and need are sufficient, they might also support a suite of related, intensive studies, as was supported in Canada by the Industrial Chair Research Grants. On the Plateau, this might be a suite of studies focused on the interactions among temperature, precipitation, nutrition, and pathogen activity.

CONCLUSION

If we face the future without changing the way we do business, forestry and forestry research resources are inadequate to address the complex and rapidly changing factors that will influence the sustainability of northern hardwood forests. With inaction, we risk failing to recognize, understand or adapt to the changes that we know are coming. Yet within the northern hardwood region, differences in the makeup and capacity of the forest management sector abound. State agencies have different capacities to fund forest ecosystem and management research. Similar variations are found in the NGO and industrial sectors. The composition of the research community varies as well, based on the number and nature of universities in the region and on the orientation of the Forest Service research labs found there. The model proposed here is flexible enough to meet this variability with creative engagement of scientists and managers who want to work together.

Science-management cooperation offers a substantially more hopeful model for facing this future. When scientists collaborate with managers in a formal, adaptive management framework—including disciplined and sustained support to monitor the outcome of management strategies targeted at expected changes—and adapt accordingly, and when managers and scientists work together to identify and fund research to address the most pressing mechanistic hypotheses, the probability of managing sustainably in the face of these changes increases dramatically.

In fact, when we look realistically toward the future, science-management collaboration is not just an option—it's essential.

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REGENERATION AND BIOTIC INTERFERENCE

Preharvest Stand Regeneration Composition and Associated Driving Factors

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INTRODUCTION

Concerning trends in natural tree regeneration emerged over the last few decades following a long history of single-tree selection silviculture in northern hardwood forests. Regeneration in these systems varies geographically and is often inadequate. For example, sapling classes may be understocked, absent, or dominated by a few relatively undesirable species (e.g., American beech [*Fagus grandifolia*], ironwood [*Ostrya virginiana*]). Multiple interacting factors may explain these troubling regeneration patterns, including silvicultural practices that provide insufficient light/disturbance, competition from shrubs and undesirable advance regeneration, site quality, seed availability, and browsing from high white-tailed deer (*Odocoileus virginianus*) populations. Understanding where regeneration is failing under single-tree selection and associated predictors is key for guiding future management, including implementation of alternative harvesting regimes. We aim to characterize overall species diversity of tree regeneration and patterns of species distributions in northern hardwood forests managed by single-tree selection. We hypothesize that deer use and high basal area correlate with low densities of desirable species and that overall species diversity is low.

METHODS

Drawing on a dataset of 141 northern hardwood stands throughout northern Michigan, we analyzed patterns of tree regeneration composition, structure, and diversity following decades of management by single-tree selection. Data were collected in summer 2017 to quantify vegetation, with 25 survey points per stand, and variable radii fixed-area plots at each survey point. We also conducted deer-pellet transect surveys to assess winter deer use in spring 2017. We conducted generalized linear modeling using a Bayesian framework to assess how stand-basal area, stand-basal area heterogeneity, winter deer use, conspecific-canopy density, and shrub coverage associate with stem densities of individual species for key regeneration size classes. For each species $\times$ size class, we compared a negative binomial distribution versus a zero-inflated Poisson model and chose the model with the superior deviance information criterion (DIC).

RESULTS

Overall, species diversity was low in our stands. We had 29 tree species present in our stands (excluding woody shrub species) across all size classes. Species diversity measures were uniformly low and mean species richness declined with increasing regeneration size class. Individual species models revealed associations which matched species' autecologies and notions regarding limiting factors in northern hardwood forests. For seedlings (i.e., stems <50 cm tall), we saw positive

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associations between seedlings and conspecific counts of sawtimber (i.e., stems > 24 cm d.b.h.) for most species, including sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and basswood (*Tilia americana*). Species which typically have lower maximum diameters had positive associations with conspecific poletimber (i.e., 11–24 cm d.b.h.) counts, such as ironwood and balsam fir (*Abies balsamea*). These results suggest local seed sources limit seedling density. For saplings (i.e., >50 cm tall and <5 cm diameter at breast height), we saw similar positive associations with conspecific poletimber and sawtimber stem counts. There were also negative associations with total stand basal area for key species such as sugar maple, red oak (*Quercus rubra*), and cherry species (*Prunus* spp.), and negative associations with sugar maple and yellow birch with winter-deer use. Deer use was positively associated with density for some species undesirable for management, including ironwood and ash.

Our results suggest that alternative management is needed throughout much of the range of northern hardwood forests in northern Michigan. Evidence suggests winter-deer browsing may be selectively inhibiting regeneration, particularly saplings (i.e., >50 cm tall and <5 cm diameter at breast height). Northern hardwood forests in regions of high deer populations may be particularly difficult to effectively manage. However, strategies such as leaving tops as barriers to browsing may be effective at promoting regeneration establishment and recruitment. Our results also indicate that basal area may negatively influence regeneration density, given the negative associations between stand-basal area and several key species. Harvests that remove a greater percentage of a stand's basal area may promote more diverse and abundant regeneration in the future. Seed source may be limiting for many species, as seedlings were positively associated with the density of conspecific-canopy trees. Promoting greater species diversity may therefore require active seeding or planting of more diverse species in the understory, as this would indicate that a species-poor canopy is likely to promote species-poor tree regeneration. These data can be used to guide future management in northern Michigan and the wider Great Lakes region.

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Early Vegetation Responses to Canopy and Soil Disturbances

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INTRODUCTION

Long-term implementation of uniform silvicultural systems can reduce species (Crow et al. 2002, Leak and Sendak 2002, Schulte et al. 2007) and structural (Angers et al. 2005, Hupperts et al. 2018, Montes et al. 2005) diversity. Diversity loss leads to less resilient forest ecosystems (Holling 1973), especially with increasing challenges due to climate change. Implementation of natural disturbance-based management could be beneficial for biodiversity by emulating natural stand conditions that prevailed before the species decline (Hupperts et al. 2018). Therefore, we sought to answer the question: Can artificial soil disturbance and the removal of canopy trees sufficiently emulate natural disturbances and create suitable seedbeds for declining tree species in a managed Great Lakes northern hardwood forest? To address this objective, an experiment was established with three different levels of soil disturbance nested within four different levels of residual canopy.

METHODS AND RESULTS

To investigate the utility of novel silvicultural approaches, we conducted the research on the 111 acres spanning the Northern Hardwoods Silviculture Experiment to Enhance Diversity (NH-SEED) research trial at the Ford Forest Research Center in Albion, MI (46°37', 88°29'W). The average daily temperature (1981–2010) ranges from –10.8 °C in January to 18.1 °C in July for a yearly average of 4.7 °C. The annual total precipitation 2007–2016 averaged 88.9 cm, including considerable annual snowfall averaging 390.1 cm (NOAA 2016). The site is dominated by sugar maple (*Acer saccharum* Marsh). Other common species are red maple (*Acer rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), eastern hemlock (*Tsuga canadensis* L.), balsam fir (*Abies balsamea* L.), black cherry (*Prunus serotina* Ehrh.), eastern white pine (*Pinus strobus* L.), ironwood (*Ostrya virginica* Mill.), trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), and white spruce (*Picea glauca* Voss).

The nested experiment was designed as a Before-After-Control-Impact (BACI) experiment, set up in a randomized complete block (RCB) design. Four different levels of canopy removal and three different levels of soil disturbance were implemented over a total of 54 treatment units, each ~2 acres in size, in 2016/2017. The canopy removal treatments are clearcutting three replicates) shelterwood with either 30 percent or 60 percent residual canopy (six replicates each) and single-tree selection as control treatment (three replicates). Nested in every canopy treatment unit are three different levels of soil disturbance: untreated control, soil scarification, and artificial tip-up mounds. The initial harvest was applied in February and March 2017 with a cut-to-length system. Saplings (>30 cm in height but <5 cm d.b.h.) were removed in August 2017 in all treatments but the singletree selection. The artificial tip-up mounds were implemented during the initial harvest

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by pulling about 30 trees per acre out of the ground and placing the root ball within ~5 m of the created pit. Soil scarification was implemented using a salmon blade in October 2017.

A setup of two randomly placed circular 3 m² plots in each of the 54 treatment units showed initial vegetation response during the first two years following treatments (Hupperts et al. 2020). Seedling (< 30 cm tall) tallies for all species were taken in each plot during the growing season in 2016 (one growing season pretreatment) and 2018 (two growing seasons post-treatment). Also several environmental variables (i.e., canopy openness, litter depth, soil water content, cover of exposed soil and coarse woody debris, and residual overstory basal area) were measured. Overall, silvicultural treatments had little relation to seedling density. Only sugar maple seedling density was related to silvicultural treatments and was lower in clearcuts as compared to other canopy treatments ($\chi^2 = 12.484$, $p > \chi^2 = 0.006$). Sugar maple seedling density displayed a marginally significant relationship with soil treatments ($\chi^2 = 5.621$, $p > \chi^2 = 0.060$) and tended to decline or have greater variation in scarification treatments. Yellow birch seedling density was not statistically related to silvicultural treatment. In contrast, the authors found microsite variables postharvest to be correlated with seedling density for three tree species. In their experiment, yellow birch seedling density was positively correlated with litter depth variation ($z = 2.244$, $p = 0.029$), and the basal area of residual mature yellow birch trees in the stand had a slight positive effect on yellow birch seedling density ($z = 1.940$, $p = 0.053$). Canopy openness was found to be negatively correlated with red maple ($z = -2.487$, $p < 0.015$) and sugar maple ($z = -3.352$, $p < 0.001$) seedling density. Average litter depth, exposed soil cover, coarse woody debris cover, and soil water content were not significantly correlated with seedling densities in this experiment.

While the study conducted by Hupperts et al. (2020) investigated the effect of different nested treatment combinations, none of the randomly placed plots were actually positioned on artificial tip-up mounds. In 2017, to study vegetation dynamics on actual mounds within the canopy treatments we randomly chose 66 artificial tip-up mounds (12 in clearcuts, 20 in single-tree selection, 17 in each shelterwood) and set up a permanent 3 m² plot on each. These were compared to 36 untreated control plots. Cover of ground layer vegetation (i.e., herbaceous, shrub, grass, sedge, rush, nonvascular), exposed soil, exposed rock, leaf litter, and coarse woody debris, as well as the seedling and sapling abundance by species have been monitored yearly during the growing season since 2017. Physical properties of the tip-up mounds were also measured in 2017 after implementation and remeasured in 2021 to document change in mound size and shape over time.

Preliminary data available from our study suggests there might be an effect on seedling abundance by artificial mounds. A nonmetric multidimensional ordination (not shown here) revealed that control plots have shifted toward less diverse species composition since the initial harvest. Red maple and sugar maple are common in areas of undisturbed soil, whereas yellow birch tends to be more common on tip-up mounds 3 years after implementation (Fig. 1). Of interest the number of seedlings in the control also went up, but there was notable high variation. Further analysis of the data will reveal if this effect might be linked to an abundance of propagules in the stand.

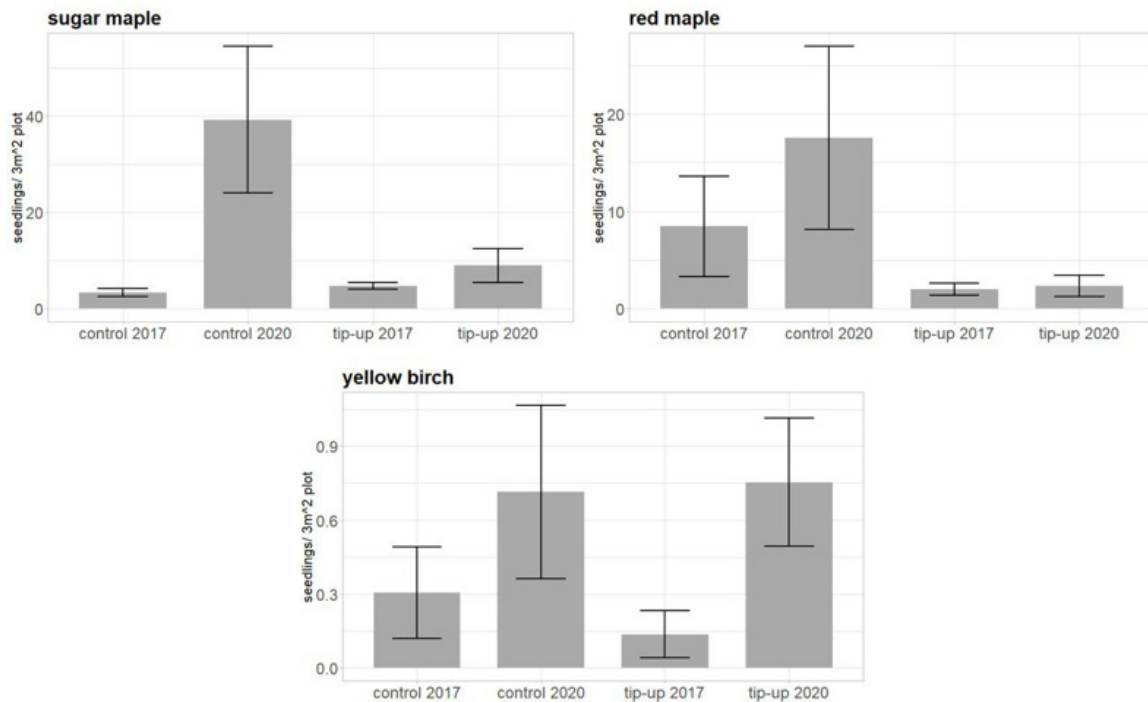


Figure 1.—Mean seedling (<30 cm tall) density and standard error on artificial tip-up mounds and control plots in a managed northern hardwood forest in upper Michigan. All data are preliminary. Note species-specific y-axis ranges. Only the three most abundant species were included.

CONCLUSION

Results reported by Hupperts et al. (2020) suggest that sugar maple will likely maintain dominance. In contrast to their hypotheses, treatments had little relation to yellow birch seedling density. Yellow birch seedling density was best predicted by residual basal area of nearby conspecific trees and within-plot litter depth variation, suggesting that propagule availability and microsite heterogeneity are more important determinants of yellow birch seedling recruitment than treatments alone. Additionally, recent preliminary findings suggest that yellow birch might benefit from reduced competition on artificial tip-up mounds. Nevertheless it will be crucial to monitor if germinated seedlings on artificial tip-up mounds will be able to successfully recruit into larger-size classes and remain competitive in the developing cohort.

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Tree Regeneration Response to Variable-Sized Group Selection Harvest Gaps in Northern Wisconsin

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Abstract.—We established a field experiment in an even-aged, second-growth northern hardwood forest in north-central Wisconsin, testing the response of tree regeneration to deer exclusion and group-selection harvesting where small (50 m²), medium (200 m²), and large (380 m²) gaps were created. We measured occurrence and height of saplings 9 years post-treatment and modeled incoming solar radiation in gaps to assess light distribution across the gap environments.

Densities of tolerant and midtolerant saplings were similar in medium and large gaps but tolerant saplings outnumbered midtolerants approximately four to one in small gaps. However, tolerant saplings averaged two meters taller than midtolerants across gap sizes. Deer exclusion increased midtolerant-sapling density but did not influence tolerant-sapling density. Modeled light levels decreased with gap size and varied by position within gaps. We attribute the increases in tree diversity in gaps over 200 m² to higher light levels across medium and large gaps.

INTRODUCTION

Long-term implementation of group selection harvesting (GSH), a gap-scale silvicultural system in which groups of overstory trees are harvested to emulate canopy-gap formation following natural disturbances of low-to-moderate severity, can create complex mosaics of differing even-aged conditions at the stand scale (Palik et al. 2020). Although not widely implemented in the Great Lakes region, GSH can increase structural and compositional diversity in northern hardwood forests. These attributes are particularly important as both can improve ecosystem function and may increase ecosystem resilience and adaptability (Ehbrecht et al. 2017, LaRue et al. 2019, Messier et al. 2013, Peuttmann et al. 2012).

Prior research from The Flambeau Experiment has already demonstrated sapling densities and species diversity are higher in gaps relative to controls (Forrester et al. 2014, Sabo et al. 2019). Here we use the infrastructure of the Flambeau Experiment to test the effect of three different GSH gap sizes and deer-exclusion fencing on sapling (d.b.h. ≥ 0.5 cm, height ≥ 1.37 m) density and total height of shade-tolerant and midtolerant tree regeneration 9 years post-treatment. We also model incoming solar radiation to test the assumption of resource heterogeneity within and between our GSH gaps, which approximately span the range of gap sizes that form naturally in northern hardwood forests of the Great Lakes region (LS-NH) following frequent disturbances of low to moderate severity (Bolton and D'Amato 2012, Frelich and Lorimer 1991, Palik et al. 2020, Schliemann and Bockheim 2011, Woods 2004). Studies which quantify the density and height variation among saplings of different shade-tolerance classes nearly a decade after harvest—and characterize light availability across several gap sizes—will help inform future implementation of gap-based regeneration methods in LS-NH.

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MATERIALS AND METHODS

This study was conducted in an even-aged, northern hardwood stand in the Flambeau River State Forest of north-central Wisconsin, United States (45.617778, -90.785556), that regenerated following clearcut harvesting in the mid-1920s. The rich site supports a stand dominated (>50 percent basal area) in all cohorts by *Acer saccharum*, with other associates of LS-NH occupying less than 16 percent of the basal area each (Forrester et al. 2014). Deer density averaged 8–12 deer km⁻² (Robert Rolley, Wisconsin Department of Natural Resources as cited in Sabo et al. 2019). Fifteen 80×80 m plots randomly placed throughout the stand contain three nested and randomly situated but nonoverlapping-circular subplots in which small (50 m²), medium (200 m²), and large (380 m²) canopy gaps were harvested in January 2007. Deer exclosures were installed around the perimeter of five plots creating categorical treatments of subplot size (hereafter “gap size”) and deer exclusion.

In summer 2016, species and d.b.h. (cm) were recorded for all saplings within the subplots. Sapling heights (m) were subsampled by dividing the subplots into cardinal-direction-oriented quadrants and recording the height of the three tallest saplings of each species within each quadrant. Ground-level percent solar radiation was estimated within the gaps using the Voxel Octree Solar Toolkit (VOSTOK; Bechtold and Höfle 2020). We accounted for the potential effects of shadow casting from surrounding vegetation by converting vegetation points of an airborne light detection and ranging (LiDAR) point cloud of the study area into cubic voxels with dimensions of 0.85 m. Solar radiation was estimated at LiDAR ground points by ray-casting modeled solar radiation across the study area as influenced by solar angle at the study location over the growing season.

We used nested generalized linear mixed models (GLMMs) with linear negative binomial (Hardin and Hilbe 2007) and Gaussian distributions with log and identity link functions to test effects gap size, deer exclusion, and shade tolerance on sapling density (tph) and height (m), respectively. Although sapling data were recorded by cardinal-direction-oriented quadrants, our sample of only 15 replicates of each gap size, coupled with an absence of midtolerant saplings from over 25 percent of quadrants, prevented incorporating quadrant as a fixed effect in the density or height models. We therefore simplified our models by combining the values for quadrants in each gap to calculate our response variables of subplot-mean sapling density and height. To test for differences in percent-solar radiation (hereafter “light”) within and across gap sizes, we subdivided subplots into five section locations: Center, North, South, East, and West. These section locations were selected based on gradients of light reported in other gap studies from similar latitudes (Canham et al. 1990, Kneeshaw and Bergeron 1999, Gendreau-Berthiaume and Kneeshaw 2009, Marquis 1965). Scalar values of solar radiation associated with the point cloud of ground points within each section were averaged and converted to percentage of maximum in the study area. These values were used as a response variable in a GLMM with a beta distribution and logit link function to test the effects of gap size and section location on light.

RESULTS

A significant ($p < 0.001$) interaction between gap size and shade tolerance showed that midtolerant sapling regeneration, dominated by *Fraxinus* spp. (65 percent), was less frequent in small subplots than in either medium or large subplots ($p \leq 0.002$) but the densities of midtolerants in medium and large subplots were similar ($p > 0.9$; Figure 1). Densities of tolerant saplings, predominately *Acer saccharum* (66 percent), were similar ($p \geq 0.63$) across the three subplot sizes (Fig. 1). Though tolerant saplings outnumbered ($p = 0.003$) midtolerants in small subplots, densities of both tolerance classes were more variable among large and medium gaps and did not differ significantly between tolerance classes ($p > 0.8$ for all). Deer exclusion influenced ($p = 0.054$) density patterns, with fewer midtolerant than tolerant saplings occurring in unfenced plots ($p \leq 0.004$). Mean height

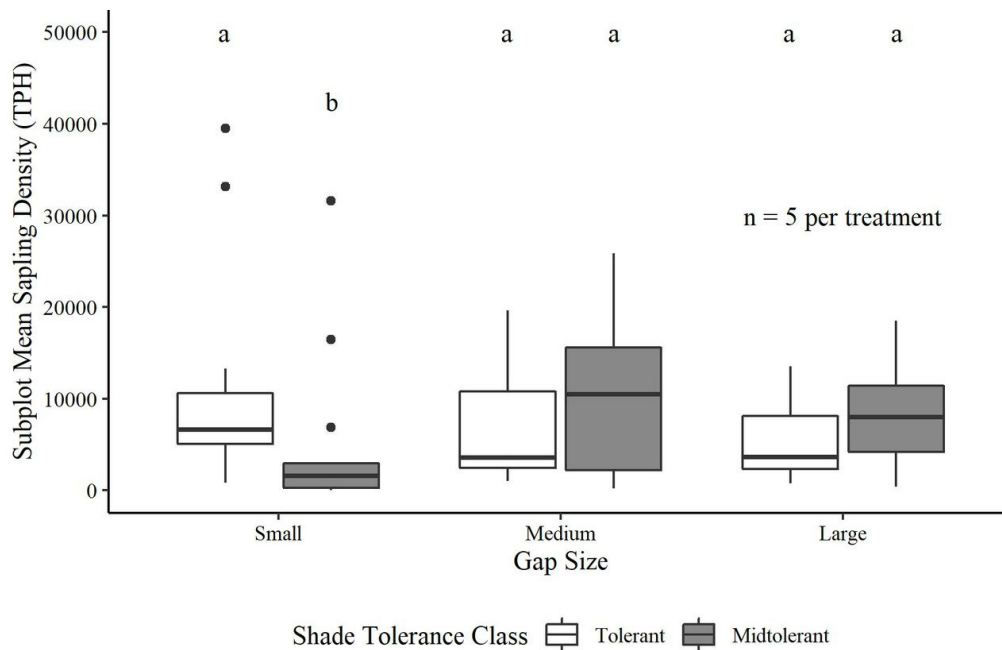


Figure 1.—Pairwise comparisons of the gap size × shade tolerance class interaction on subplot-level estimated marginal mean sapling density (TPH). Boxes not connected by the same letter are significantly different at an $\alpha = 0.05$.

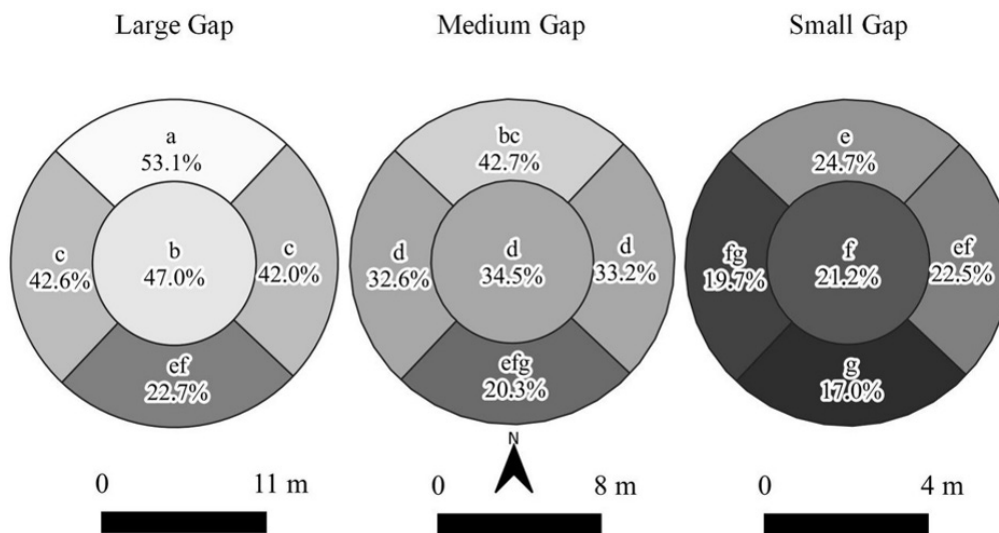


Figure 2.—Pairwise comparisons of percent direct solar radiation by gap size and section. Polygons of different colors and not connected by the same letters are significantly different at an $\alpha = 0.05$. Note the differences in scales among gap sizes.

differed between the two tolerance classes ($p < 0.0001$), with mean height among tolerant saplings (6.8 m) averaging over 2 meters taller than midtolerant saplings (4.6 m) ($p < 0.0001$), but height was not significantly impacted by gap size for either tolerance class ($p \geq 0.21$).

A significant interaction between gap size and subplot-section location ($p < 0.0001$) revealed greater light intensity with increasing gap size ($p < 0.0001$) and from north to south, regardless of gap size ($p < 0.0001$; Fig. 2). Light levels in eastern and western sections were often different than northern or southern sections, although the significance of differences dissipated with gap size (Fig. 2). The range of light values also declined with gap size from a range of approximately 30 percent in large gaps to less than 8 percent in small gaps. The patterns are interesting and complex,

yet considerable overlap in light levels occurred within and across gap sizes depending on the sections being considered. For example, light in the center of large gaps was equivalent to light in the northern portions of medium gaps ($p = 0.8$) and light in the southern sections of large gaps was similar to light in the northern section of small subplots ($p > 0.9$).

DISCUSSION AND CONCLUSIONS

Our results generally agree with some (Forrester et al. 2014, Kern et al. 2013, Knapp et al. 2019a, Knapp et al. 2019b, Knapp et al. 2021, Sabo et al. 2019) but differ from several other gap-based silviculture experiments in LS-NH (Bolton and D'Amato 2012, Reuling et al. 2019) in that we found that GSH can be a viable regeneration approach to meet objectives related to increased tree-species diversity. Indeed, our approximately balanced ratio of tolerant and midtolerant sapling regeneration in GSH gaps $\geq 200 \text{ m}^2$ may rightfully provide some managers confidence in this regeneration approach. However, another similarity between our results and those reported by others (Bolton and D'Amato 2012, Kern et al. 2013, Knapp et al. 2019a, Knapp et al. 2019b, Knapp et al. 2021, Reuling et al. 2019) is that advance regeneration of tolerant species was released by GSH and is contributing to a 2-meter height advantage among tolerant species. Continued monitoring of regeneration in these gaps will be necessary to determine whether midtolerant species ultimately ascend to canopy positions given their current height disadvantage. Interestingly, previous research from this experiment reported that tolerant and midtolerant saplings had similar height growth rates following GSH (Forrester et al. 2014). We believe these collective findings accentuate the importance of additional research on whether implementing stand-tending practices in conjunction with GSH—such as pre- or post-harvest control of advance regeneration of tolerant species—can lead to long-term diversification in species composition.

We attribute our density-related findings to the higher light levels in gaps of at least 200 m^2 . After accounting for shadowing from surrounding vegetation, approximately 41 and 33 percent of incoming light reached the forest floor in large and medium gaps, respectively, compared to only 21 percent in small gaps. This trend, as well as our findings in support of a significant north-south gradient, was expected and agrees with trends reported in other studies of light in gaps in northern hardwood systems (Canham et al. 1990, Gendreau-Berthiaume and Kneeshaw 2009, Marquis 1965). As such, we interpreted our results as evidence that the wider ranges of higher-light levels found in medium and large gaps is more conducive to regenerating mixtures of tolerant and midtolerant saplings than the narrower range of lower-light values associated with gaps less than 50 m^2 .

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Considerations for Creating Canopy Gaps in Northern Hardwood Forests

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INTRODUCTION

For over 60 years, northern hardwood stands across the Great Lakes region have primarily been managed using single-tree selection (Tubbs 1977) in which a thinning is applied uniformly across a stand to reach a desired target basal area and diameter distribution. While this form of silviculture can create high quality, shade-tolerant trees, it can also create stands that lack diversity of structure and function (Neuendorff 2007). Increasingly, foresters are looking to manage northern hardwood stands for greater diversity and increased resilience to stressors such as climate or insect outbreaks. Past studies on group selection have shown benefits beyond producing timber, such as increased diversity of songbirds (Costello et al. 2000), fungal species (Dove and Keeton 2015), and insect pollinators (Proctor et al. 2012). Using group selection to increase diversity of tree regeneration can produce highly variable results (Knapp et al. 2021). Some reasons why group selection results could vary include the location and size of the gaps, as well as whether to remove all trees in the gap or leave saplings.

METHODS

In 2007, three northern hardwood stands across Wisconsin (i.e., Argonne, Flambeau, and Highlands) were selected for a large silviculture experiment called the Managed Old-Growth Silviculture Study (MOSS) (Fassnacht et al. 2015). Part of the MOSS experiment was to investigate group selection harvests to study short-, mid-, and long-term seedling responses. Two gap sizes of 18 and 24 m (i.e., 59 and 79 ft) diameter were created within the group selection stand. Gap size was randomly assigned at each desired gap location. There were a total of 14 and 12 gaps of 18 m created at Flambeau, Highlands, and Argonne, respectively. Similarly, there were a total of 14 and 12 gaps of 24 m created at Flambeau, Highlands, and Argonne, respectively. Additionally, half of the gaps had a nested treatment of sapling retention, while the remaining gaps had a nested treatment of sapling removal. In 2012, the 3-year post-harvest data were collected and evaluated (Reuling et al. 2019). In 2017, the 10-year post-harvest tree regeneration was measured, analyzed, and herein reported.

The considered response variable was stem density of tree regeneration, but the species of that tree regeneration were binned into two categories. The first category was called less shade tolerant tree species, which consisted of *Acer rubrum*, *Carya cordiformis*, *Betula alleghaniensis*, *Betula papyrifera*, *Fraxinus* spp., *Pinus strobus*, *Populus tremuloides*, *Prunus serotina*, *Quercus rubra*, and *Ulmus americana*. The second category was called merchantable tree species, which consisted of the less shade-tolerant tree species plus *Acer saccharum*, *Tilia americana*, *Tsuga canadensis*, and *Picea glauca*.

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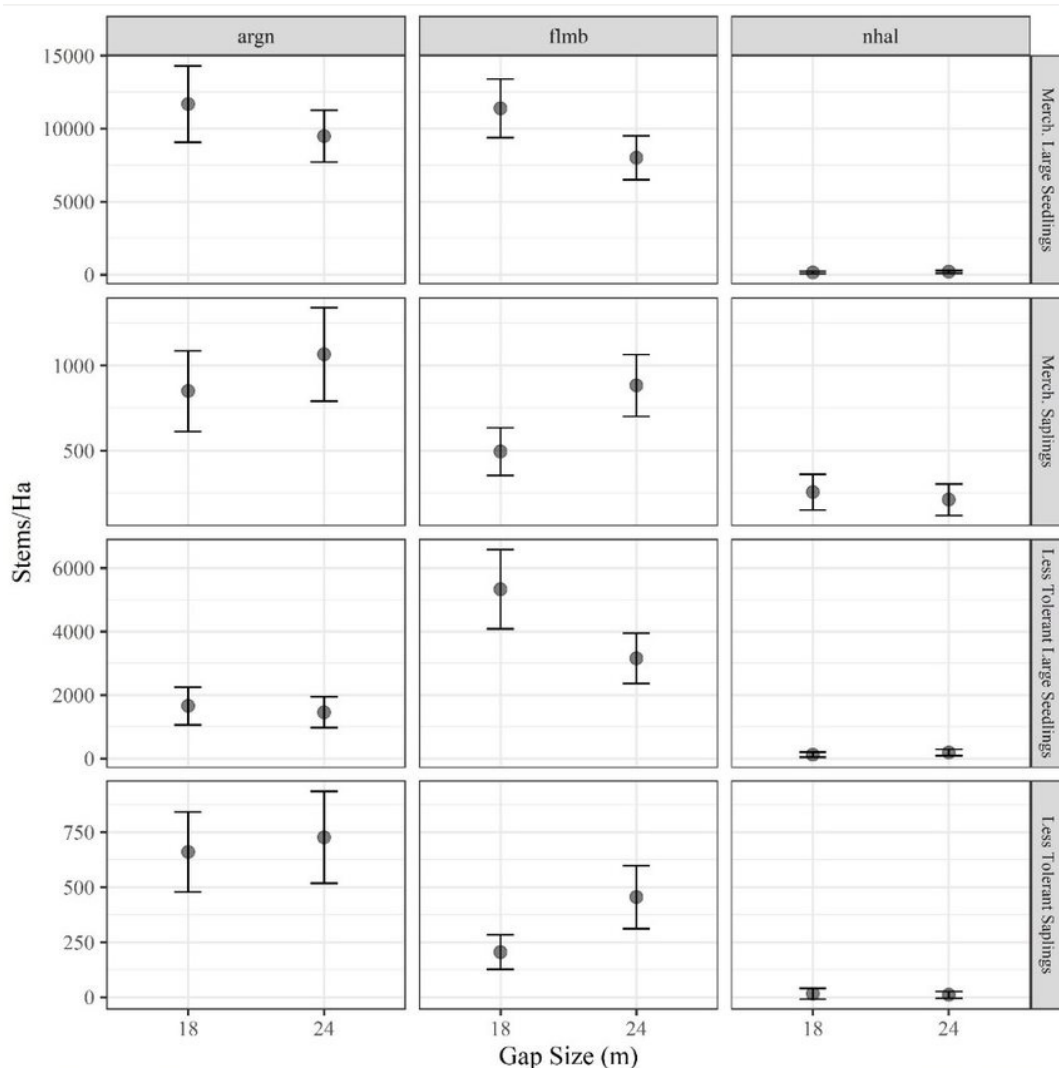


Figure 1.—Stem density for the two gap sizes and across the three sites Argonne (argn), Flambeau (flmb), and Highlands (nhal). Stem density is reported by merchantable and less shade-tolerant tree species for large seedlings and saplings.

RESULTS

Results showed that the effect of gap size and sapling retention had varying outcomes across the three sites. Specifically, tree regeneration of all tree species was significantly greater in 18 m gaps compared to 24 m gaps, but only at the Flambeau site, not Argonne or Highland sites (Fig. 1). The sapling removal treatment created a greater amount of regeneration for all tree species, but only at the Argonne site, not Flambeau or Highland sites (Fig. 2). The Highland site, which had the lowest amount of advance regeneration preharvest in 2007 continued to have poor regeneration in 2017 even with a group selection harvest. Neither gap size nor sapling removal were significant in explaining regeneration at Highlands.

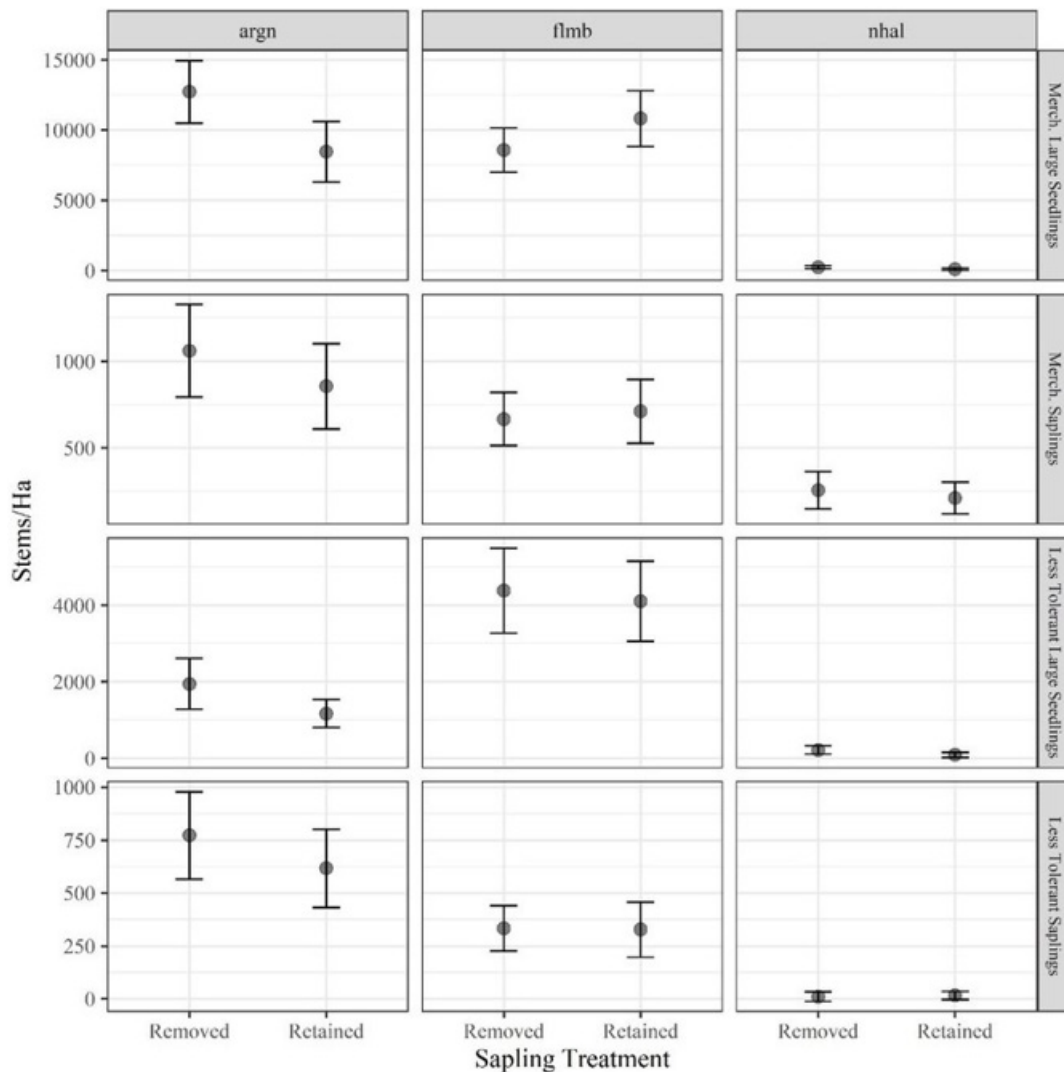


Figure 2. —Stem density for the two sapling treatments and across the three sites Argonne (argn), Flambeau (flmb), and Highlands (nhal). Stem density is reported by merchantable and less shade-tolerant tree species for large seedlings and saplings.

DISCUSSION

Group selection for the Highland site was not a successful harvest strategy for tree regeneration. This result at the Highlands may be explained by having lower nutrient sandy soils compared to Flambeau and Argonne sites. We question whether sandy sites like Highlands should continue to be managed for northern hardwoods or would benefit from conversion to other forest types such as oak and pine. In contrast, group selection produced tree regeneration that met or exceeded stocking standards on the more productive sites (i.e., Argonne and Flambeau). It is interesting the Flambeau site showed differences in tree regeneration between gap sizes but not the Argonne site, and the Argonne site exhibited differences with the sapling treatment but not the Flambeau site. Changes in light availability and microclimate from either gap size or the presence of a sapling mid-layer certainly can alter tree regeneration, but numerous other factors also contribute to results. Soil conditions, herbaceous competition, and presence of browsing from white-tailed deer (*Odocoileus virginianus*) are important when considering tree regeneration. Future analyses will focus on these factors and how their interactions may have contributed to final outcomes.

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Group Selection Opening Effects on Regeneration Decades after Harvest

Christel C. Kern, Samuel P. Knapp, Matthew S. VanderMolen, and Christopher R. Webster¹

Abstract.—Forest managers and researchers have proposed group selection as a complementary system to conventional, uneven-aged management in temperate hardwood forests with the goal of counteracting declines in forest diversity (Eyre and Zillgitt 1953, Leak and Sendak 2002, Neuendorff et al. 2007). The intended goals for group openings in this selection system are to establish new age classes and use opening size to influence essential resources and microclimates in openings to complement the desired species composition of regeneration (Coates and Burton 1997, Grubb 1977, Lhotka et al. 2018). Yet few long-term studies provide group selection outcomes (Coates and Burton 1997, Kern et al. 2017).

INTRODUCTION

These findings present tree regeneration results from two long-term group-selection experiments implemented in northern hardwood forests in the western Great Lakes region.

METHODS

We used two experiments: (1) Divide Canopy Gap Study (DCGS), Chequamegon-Nicolet National Forest, Forest County, Wisconsin (N 45°56', W 88°59') and (2) Yellow Birch Legacy-tree Project (YBLP), Michigan Technological University's Ford Center and Forest, Baraga County, Michigan (N 46°37', W 88°29') (Table 1).

The DCGS has a randomized, complete-block design. Treatments were six size classes of harvest-created, circular-canopy openings (Table 1). The remainder of the study site was thinned (except in the reference [0 m] sites where no harvesting occurred). The YBLP has a completely randomized design. In 2003, the study area was surveyed for dominant and codominant yellow birch and 69 were randomly selected to serve as centers of four size classes of harvest-created, circular-canopy openings and reference sites (0 m, Table 1). The species selection for legacy-tree retention was yellow birch (*Betula alleghaniensis* Britton) because this historically important species is scarce in the area. Legacy-tree retention maintains overstory presence and seed source in the stand over multiple cutting cycles. The remainder of the study site was treated with single-tree selection.

We used regenerating tree species, size, and density over time to study composition and density, sapling structure and composition, and failed regeneration patches across opening size classes at each experiment. Accompanying studies of browse were conducted for each site. Exclosures were maintained for a short, early period at the DCGS and in a gap study of similar duration at and near the YBLP. Data were analyzed by experiment. For details on methods, see Knapp et al. 2019a, Knapp et al. 2019b, Knapp et al. 2021, VanderMolen et al. 2021, and VanderMolen and Webster 2021.

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Table 1.—Study design and site details for two long-term group selection experiments in northern hardwood forests of the western Great Lakes, United States

Study design and site characteristics	Divide Canopy Gap Study (DCGS)	Yellow Birch Legacy-tree Project (YBLP)
Location	Northern Wisconsin, United States	Upper Michigan, United States
Habitat type	ATD	ATD
Soil type	sandy loam	silt loam
Known management history since 1900	Unmanaged since clearcut ca. 1930s	Heavy partial cut 1938; Single-tree selection since 1954
Year(s) of study establishment	1994-1995	2003
Stand age structure at establishment	Even-aged forest (approx. 60-years-old at study establishment)	Uneven-aged (4+ age classes)
Legacy-tree retention with group opening	No	Yes
Tree d.b.h. (cm) harvested	>2.5	>10
Data collected (years post-harvest)	23–24	15–18
Group opening radius (m) (no. of replicates)	0 ([reference, uncut], 12) 3 (11) 5 (11) 10 (11) 20 (12) 23 (12)	0 ([reference, single-tree selection], 20) 11 (16) 16.6 (17) 22 (16)

RESULTS AND DISCUSSION

We first investigated regeneration layer density in openings at both experiments one to two decades after harvest. In general, seedling and sapling densities were higher in openings than references at both experiments (Table 2; Knapp et al. 2019a, 2021). At DCGS, sapling density was largely at acceptable levels for sustainability, except in large openings (i.e., 46 m diameter) where 23 years after harvest regeneration density was low and > 40 percent of our sample plots (i.e., 1.83 m radius) were considered regeneration failures (without trees taller than 1.37 m; Knapp et al. 2021). At YBLP—where legacy trees were retained—opening size did not affect rates of within-opening regeneration failures 15 years after harvest; frequency of regeneration failures was similar to DCGS. Regeneration failures were not related to resource and microclimate gradients within openings at either experiment (VanderMolen et al. 2021). Rather, using data from DCGS, regeneration densities at year 23 after harvest were best predicted by the observed densities at year 2 after harvest (Knapp et al. 2021). Earlier research at DCGS documented thick *Rubus* spp. cover in large openings (Kern et al. 2013). At YBLP, previous research showed *Rubus* patches resisted reinvasion by trees for over a decade (Widen et al. 2018). The research at both experiments demonstrated the importance of advance regeneration at the time of harvest when additional treatments are not planned (e.g., scarification, artificial regeneration).

We next investigated the composition and diversity of regeneration when present at both experiments one to two decades after harvest. Richness and evenness were not different across opening sizes at either experiment (Table 2; Knapp et al. 2019a, 2021). Species richness was low (i.e., 1 to 3 species) at DCGS 23 years after harvest (Knapp et al. 2021). Species richness was

Table 2.—Summary of results from two long-term group selection experiments (See Table 1 descriptions)

	Reference	Smaller Opening Sizes	Larger Opening Sizes	(Citation)
Density, all regeneration				(Knapp et al. 2019a, 2021)
DCGS, 23 years after harvest	Low	Acceptable	Some failures	
YBLP, 15 years after harvest	Low	Acceptable	Some failures	
Diversity, all regeneration				(Knapp et al. 2019a, 2021)
DCGS, 23 years after harvest	Low	Low	Low	
YBLP, 15 years after harvest	Low	Moderate-Low	Moderate-Low	
Composition, all regeneration				(Knapp et al. 2019a, 2021)
DCGS, 23 years after harvest	Sugar maple	Mix of sugar maple, ironwood, white ash	Mix of sugar maple, ironwood, white ash	
YBLP, 15 years after harvest	Sugar maple	Sugar maple with some red maple	Sugar maple with mix of red maple, yellow birch	
Composition, gap-capturing saplings				(Knapp et al. 2019b)
DCGS, 23 years after harvest	Sugar maple (overstory)	Mix of sugar maple, ironwood, white ash	Mix of sugar maple, ironwood, white ash	
YBLP, 15 years after harvest	Sugar maple with mix of eastern hemlock and yellow birch (overstory)	Sugar maple with mix of red maple, black cherry, ironwood	Sugar maple with mix of red maple, black cherry	

moderately low (3 to 5 species) across opening sizes at YBLP 15 years after harvest. However, at YBLP openings had slightly more species (i.e., 1+ species) and diversity (i.e., Shannon’s Diversity Index and evenness) of regenerated seedlings compared to references 15 years after harvest. YBLP also showed some compositional differences that were not detected at DCGS; YBLP openings with legacy-tree retention were commonly composed of red maple (*Acer rubrum* L.) and yellow birch in addition to dominant sugar maple (*Acer saccharum* Marsh.). Moreover, red maple regeneration was frequently >1 m tall, while yellow birch regeneration was rarely over 2 m tall 15 years after harvest (Knapp et al. 2019a). Companion studies of deer exclosures at the DCGS and near the YBLP indicate ungulate browsing is likely influencing composition in openings at both experiments (Kern et al. 2012, VanderMolen and Webster 2021). For example, 18 years after harvest, browse sensitive species >1 m tall were frequent inside but rare outside exclosures existing on the same land base as the YBLP (VanderMolen and Webster 2021). The research at both experiments demonstrated varying opening size alone had minimal effects on regeneration diversity and composition. Legacy-tree retention was correlated with compositional shifts; however, deer browsing is likely a major filter for regenerating tree composition as saplings ascend toward the canopy.

Given the results stated above, we lastly investigated only the saplings with the best potential to attain a canopy position—the tallest saplings within an opening (hereafter “gap-capturing saplings”). Only one or a few saplings are needed to eventually fill a small canopy gap and the composition of these tall saplings may not reflect the general trends we observed in the assessments of the full regeneration layer. Gap-capturing sapling composition did not match the surrounding canopy dominated by sugar maple at either experiment, and opening size had limited effects on sapling diversity (Table 2; Knapp et al. 2019b). At DCGS, 23 years after harvest, we found—regardless of opening size—that gap-capturing sapling composition was dominated by sugar maple, ironwood (*Ostrya virginiana* [Mill.] K. Koch) and white ash (*Fraxinus americana* L.), which was similar to the advance regeneration composition remaining at year two post-

harvest. Because of the lethal effects of anticipated emerald ash borer (*Agrilus planipennis*) on ash trees and the subtree growth form of ironwood to fill lower canopy positions, future canopy composition is not expected to change significantly over the next several cutting cycles. At YBLP, openings were dominated by sugar maple 15 years after harvest but opening size moderately affected composition. Large openings had more shade mid-tolerant red maple (*A. rubrum* L.) and intolerant black cherry (*Prunus serotina* Ehrh.). Large opening composition was different from the surrounding canopy, which had more eastern hemlock (*Tsuga canadensis* [L.] Carrière) than regeneration layers. This compositional deviation between gap-capturing saplings and surrounding canopy trees may alter canopy composition over several cutting cycles (Knapp et al. 2019b). Yellow birch was not a significant part of opening composition, despite yellow birch left as legacy trees and localized seed sources in all YBLP openings. Yellow birch regeneration was significantly aggregated across spatial scales and tended to occur at higher abundance in the shade of the legacy tree and along the southern edges of openings (Poznanovic et al. 2014). YBLP openings were not scarified after harvest, therefore, lack of suitable substrate may have limited yellow birch establishment (Caspersen and Saprunoff 2005, Willis et al. 2016).

The varying outcomes between these experiments may be due to available seed sources, legacy-tree effects, browsing intensities, stage of stand development, and management histories that differed between the sites (Table 1; Knapp et al. 2019b). More broadly, contemporary ecosystems such as these are experiencing significant challenges to resilience due to an array of legacy, ongoing, and novel factors (Webster et al. 2018). Continued study and evaluation of silvicultural tools across a range of site conditions and time frames is essential.

CONCLUSIONS

Theory predicts that group selection openings should promote increased recruitment of shade-intolerant and midtolerant species in temperate hardwoods, but our experimental results suggest that opening creation alone only modestly affected diversity and more broadly resulted in regeneration failures in large openings. Legacy-tree retention in gaps was associated with some opening-size effects, including more light-demanding species in gap-capturing saplings and slight increases in regeneration diversity in general with increasing opening size. The moderating effects of the retained tree cover may facilitate species coexistence, but more research is needed. Our results also suggest that outcomes following group selection are highly context dependent, and that factors unrelated to opening size such as management history and browsing intensity may profoundly influence results even decades after harvest. Careful placement of openings and postharvest treatments such as planting and/or browse protection might be necessary for group selection to be successful in contemporary hardwood forests in the western Great Lakes region.

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Can Postharvest Regeneration in Group Selection and Patch Cutting Predict Future Species Composition?

Simon Bilodeau-Gauthier, Steve Bédard, and François Guillemette¹

Abstract.—In Quebec, Canada, multicohort forest management in hardwood and mixedwood stands include group selection cutting and patch cutting. We assessed the success of these cuts in regenerating the intermediate shade tolerant yellow birch (*Betula alleghaniensis* Britt.; YB) at an operational scale and over a large territory using surveys conducted at 2, 5, 10, and 15 years after harvest. Regeneration of the target species was successful, with YB showing a mean stocking around 60 percent and a mean sapling density around 3,400 stems ha⁻¹ after 15 years. The relative presence of YB in 15-year-old canopy openings—a proxy for future species composition—was best predicted by that species' relative abundance, stocking based on one stem per sampling unit, and mean maximum height measured in year five (rather than year two) using smaller sampling units (6.25 m² rather than 25 m²). See Bilodeau-Gauthier et al. (2020) for further details.

INTRODUCTION

In hardwood and mixedwood stands, multicohort forest management (Hupperts et al. 2018) may be the best way to successfully regenerate tree species of intermediate shade tolerance (Raymond et al. 2018), such as yellow birch (*Betula alleghaniensis* Britt.; YB). The creation of large gaps in the canopy increases light availability (Webster and Lorimer 2002), while soil scarification provides suitable germination seedbeds (Elie et al. 2009). Evidence of the success of these methods nonetheless remains mostly the purview of experimental studies rather than operational tests (Gauthier et al. 2016).

METHODS

The present study tested two multicohort methods, group selection cutting and patch cutting, implemented in Quebec, Canada during 2000–2005 at an operational scale and over a large territory in hardwood-dominated and mixedwood stands (39 groups and 32 patches). Groups covered areas of 500 to 1,500 m² (12 to 22 m radius) while patches spanned 1 to 2 ha.

Tree species composing the forest stands prior to harvest were mainly sugar maple (*Acer saccharum* Marsh.) and YB for hardwood stands, or balsam fir (*Abies balsamea* [L.] Mill.), YB, northern white cedar (*Thuja occidentalis* L.), and spruces (*Picea glauca* [Moench] Voss. or *P. rubens* Sarg.) for mixedwood stands. Main companion species were American beech (*Fagus grandifolia* Ehrh.), red maple (*Acer rubrum* L.), paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), American larch (*Larix laricina* [Du Roi] K. Koch), and eastern hemlock (*Tsuga canadensis* [L.] Carr.). The most common competing trees and shrubs (hereafter “noncommercial species”) encountered in the regeneration surveys included pin cherry (*Prunus pensylvanica* L.), striped maple (*Acer pensylvanicum* L.), mountain maple (*Acer spicatum* Lam.), beaked hazel (*Corylus cornuta* Marsh.), bush honeysuckle (*Diervilla lonicera* Mill.), hobblebush (*Viburnum lantanoides* Michx.), red elderberry (*Sambucus pubens* Michx.), wild raspberry (*Rubus idaeus* L.), and willow (*Salix* spp.).

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We assessed the efficacy of these cuts in promoting natural regeneration of commercial hardwood trees, notably YB. Regeneration surveys were conducted at 2, 5, 10, and 15 years after harvest to tally seedlings (≥ 1 m in height) and saplings (diameter at breast height [d.b.h.] > 1 cm and ≤ 9 cm) of all woody species. Our aim was to test whether the early postharvest surveys could predict the future species composition.

To identify the best predictors, and when and how they should be measured, we compared several explanatory variables assessed in year two or year five after harvest, and in two different sizes of sampling units (2.5×2.5 m [6.25 m²] or 5×5 m [25 m²]). At the time of analysis, some sites had not yet reached 15 years of post-harvest age, thus $n = 49$ (i.e., 28 groups, 21 patches). Various statistical analyses were conducted on the data (Bilodeau-Gauthier et al. 2020), but this text focuses on the linear regressions and uses only the relative abundance (i.e., stem density of a given species relative to the total density of all woody species, including noncommercial ones) of YB in year 15 as the response variable.

RESULTS AND DISCUSSION

Regeneration Success

Our study showed that multicohort forest management that creates large or very large gaps in the canopy (group selection and patch cutting, respectively) can be generally successful in regenerating YB and other commercial tree species. All but one of the 49 sites met the threshold of 1,500 saplings ha⁻¹. All commercial species combined (Fig. 1) met the recommended density required for producing a merchantable stand (Leak et al. 1987).

YB showed a mean stocking around 60 percent and a mean sapling density of approximately 3,400 stems ha⁻¹ after 15 years. YB densities (i.e., seedlings and saplings) that were above 1,500 stems ha⁻¹ were found in 42 out of 49 sites. Densities of YB saplings were often satisfactory as well: 31 sites out of 49 had densities above 1,500 YB saplings ha⁻¹.

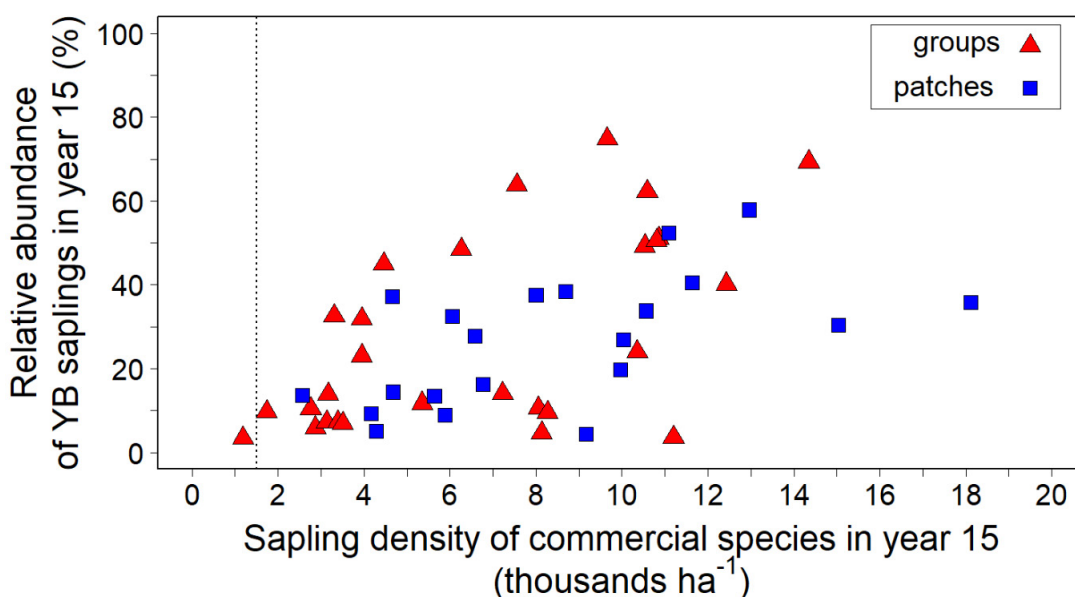


Figure 1.—Relative abundance of YB saplings (calculated in relation to the total sapling density of all woody species, commercial and noncommercial) compared to the absolute sapling density of commercial species 15 years after harvest by group selection or patch cutting. The vertical-dashed line represents the theoretical threshold of 1,500 saplings ha⁻¹ required for producing a merchantable stand (Leak et al. 1987).

Table 1.—Simple linear regressions of the relative abundance of YB in year 15 (response) with one of three different regeneration indices (explanatory) measured in year two or year five. All variables were assessed in 6.25 m² and 25 m² sampling units. Data were site means (*n* = 49). Maximum height is in cm. Relative abundance and stocking are on a scale of 0 to 100. SE: standard error

Explanatory variable	Model coefficients	Size of sampling units and year of the survey			
		6.25 m ²		25 m ²	
		Year 2	Year 5	Year 2	Year 5
Maximum height	Estimate	0.546	0.268	0.400	0.216
	SE	0.06	0.024	0.059	0.025
	<i>t</i> -value	9.03	11.1	6.75	8.54
	<i>P</i> -value	<0.0001	<0.0001	<0.0001	<0.0001
	Adjusted <i>R</i> ²	0.63	0.72	0.48	0.60
Relative abundance	Estimate	1.54	0.973	1.18	0.982
	SE	1.4	0.06	1.1	0.066
	<i>t</i> -value	1.09	16.1	1.12	15
	<i>P</i> -value	0.28	<0.0001	0.27	<0.0001
	Adjusted <i>R</i> ²	0.0037	0.84	0.0054	0.82
Stocking (1 stem)	Estimate	0.605	0.651	0.875	0.864
	SE	0.098	0.079	0.21	0.16
	<i>t</i> -value	6.2	8.21	4.26	5.24
	<i>P</i> -value	<0.0001	<0.0001	<0.0001	<0.0001
	Adjusted <i>R</i> ²	0.44	0.58	0.26	0.36

The relative abundance of YB in year 15 was almost never above 70 percent and was below 25 percent in about half the sites (Fig. 1). The spatial distribution of the desired regeneration was not always homogeneous within openings, as revealed by some low coefficients of distribution. Moreover, at some sites, noncommercial woody species still represented a nonnegligible proportion of the total sapling density in year 15 (mean = 35 percent, standard deviation = 18 percent). Consequently, a cleaning treatment meant to eliminate trees of species that are not primary targets, undertaken not past the sapling stage, might be required in the future to increase the YB proportion.

Predicting Species Composition

The linear regressions revealed that the relative abundance of YB in year 15 was best predicted by the mean maximum height, the relative abundance, and stocking based on one stem per sampling unit (Table 1). Using the year-five indices resulted in a greater number of significant relationships than with the year-two indices. Where the relationships were significant using either year, those with the year-five indices always yielded stronger coefficients of determination (*R*²). The relationships were also stronger with indices computed in smaller sampling units (6.25 m²) than in larger ones (25 m²), though in both cases the values were averaged per site.

CONCLUSIONS

Densities of commercial stems at least 1 m in height were generally satisfied according to Leak et al. (1987) stocking recommendations for commercial northern hardwood stands. Even considering YB alone, a majority of sites would have been deemed well stocked. However, the relative abundance of YB was not very high. A cleaning treatment might be considered in order to increase the relative presence of YB.

Future species composition, as represented by the relative abundance of YB within canopy openings in year 15 after harvest, was best predicted by the following regeneration indices measured in year 5 using the smaller, 6.25 m² sampling units: the mean maximum height, the relative abundance, and the stocking based on one stem per sampling unit.

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The Effects of Various Treatments on Yellow Birch Regeneration: Results from Multiple Midterm Experiments

Philippe Nolet, Steve Bédard, Pascal Rochon, Donald Blouin, and Sylvain Delagrange¹

Abstract.—In response to concerns about yellow birch (*Betula alleghaniensis* Britton; YB) regeneration in Quebec, new treatments have been tested in the 1990s, including patch cuts and small clearcuts. The objective of this project was to draw an overall portrait, at the scale of the province, on YB regeneration success 10 to 20 years after treatment. We resampled 36 experiments and 466 logging areas. The logging areas sampled were mostly dominated at the sapling stage by sugar maple (*Acer saccharum* Marsh.; SM) (23 percent) and YB (18 percent). The proportion of sites where YB was the dominant species was higher in gaps and small clearcuts than in partial cuts or controls. When we added up the proportions of YB and SM, no significant difference among treatment openings was observed. The high variability in regeneration dominance led us to conclude that, without intense monitoring, early efforts to favor YB may not be worthwhile.

INTRODUCTION

Toward the end of the 1990s, yellow birch (YB) and other mid-tolerant species regeneration arose as a concern in Quebec, as in the whole northeast United States. In response, new treatments have been tested including patch cuts and small clearcuts with or without soil scarification. In the wake of the implementation of these treatments, many experiments have been set up throughout the province of Quebec (Lorenzetti et al. 2008, Raymond et al. 2003,) and in the United States (Hupperts et al. 2020). While these tests increased our understanding of the effect of silvicultural treatments on the short-term success of YB regeneration, few results have been published on the midterm success (i.e., 10 to 20 years). For example, a quick Google® Scholar search using the terms *silviculture treatment regeneration* and *temperate* showed that, in the first 10 relevant articles, a single study had verified—over a period of more than 10 years—the effects of silvicultural treatments on regeneration (Donoso et al. 2019). In addition to the silvicultural effort (Gauthier et al. 2016), many factors—acting from the local to the regional scale—can influence the development of regeneration, including competing vegetation (Bilodeau-Gauthier et al. 2020, Raymond and Bédard 2017, Royo and Carson 2006), herbivory, and invasive species (Ward et al. 2018).

The idea behind this project was to revisit a network of 10-year-old experiments in tolerant hardwood stands in Quebec covering a range of silvicultural treatments including controls, selection cuts (minimum residual basal area of 16 m²/ha), shelterwood cuts (variable-residual basal area), patch cuts (about 0.1 ha in size) and small clearcuts (1 to 2 ha in size)—with and without scarification. The two main objectives of the project were (1) to draw an overall portrait on the midterm YB regeneration success (10 to 20 years) following the use of various types and intensities of silvicultural treatments; and (2) increase our understanding of the interaction between competition, herbivory, and abundance of short-term regeneration with silvicultural efforts on YB regeneration success.

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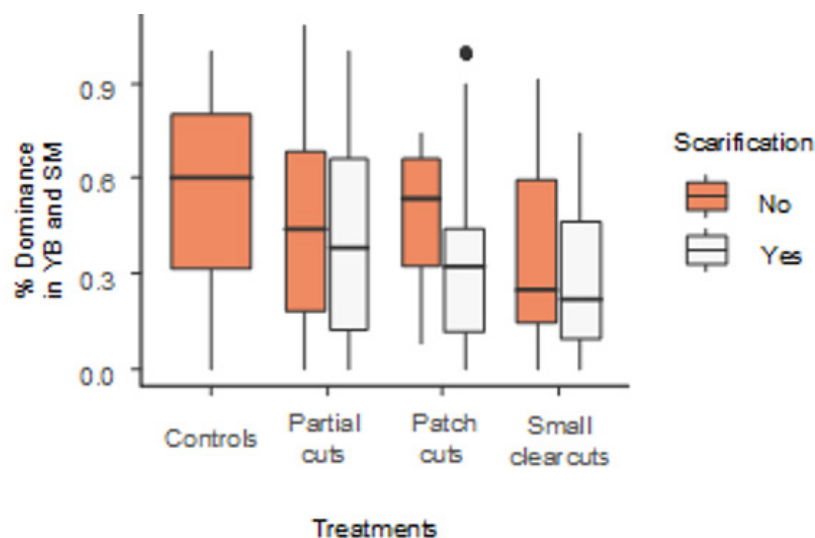


Figure 1.—Boxplots of YB and SM dominance percentage as a function of harvest treatments and scarification. The limits of the box are 25 percent and 75 percent. The separating line between the lower and upper part of the box is the median. The lower and upper limits of the whiskers are the 10th and 90th percentiles. Points are beyond 1.5× the interquartile range (25th to 75th percentiles).

METHODS

We resampled 36 experiments and 466 logging areas (including controls from various research organizations in Quebec that covered the entire tolerant hardwood region of the province). In total more than 7,000 regeneration plots (25 m²) were remeasured in which we identified the dominant species. This dominant species (commercial or noncommercial) was the one with the tallest sapling, not the most abundant. From the sampling, we calculated for each logging area: (1) for each commercial species, the proportion of plots that this species dominated, (2) for each noncommercial species, the proportion of microplots where this species dominated, and (3) the proportion of microplots where grazing was observed.

We also calculated the distance from each plot to the edge of the nearest deer-wintering habitat. Additionally, we calculated—from the inventories carried out 1 or 2 years after treatment—the initial proportion of each species at the seedling stage.

RESULTS

The 466 logging areas (including the controls) sampled were mainly dominated at the sapling stage in commercial species by sugar maple (*A. saccharum*; SM) with a dominance average of 23 percent followed by YB at 18 percent. Three other species showed an average dominance of more than 10 percent, namely beech (*Fagus grandifolia* Ehrh., 12 percent), balsam fir (*Abies balsamea* [L.] Mill., 12 percent), and red maple (*Acer rubrum*, 10 percent). The proportion of logging areas where YB was the dominant species at the sapling stage was higher in patch cuts and small clearcuts than in partial cuts and controls. On the other hand, when we added up the proportions of YB and SM (the two most valuable species), we observed no significant difference between the canopy opening treatments on regeneration dominance (Fig. 1). The short-term density of YB at the seedling stage was not a good predictor of its dominance 10 to 20 years later at the sapling stage, however the results were highly variable. For noncommercial species, mountain maple was the dominant competitor in scarified-logging areas (44 percent) while striped maple (*Acer pensylvanicum*) was the dominant species in 64 percent of nonscarified-logged areas; yet, when we reviewed the effect of these species on the dominance of commercial species, we observed few significant negative effects. No relationship was observed between the dominance of SM and YB and grazing or the distance to a deer-wintering habitat.

CONCLUSION

Our results showed that the effect of silvicultural treatments on YB regeneration are highly variable 10 to 20 years after treatments. More intense canopy openings and scarification increased YB dominance at the sapling stage but did not guarantee its dominance. Obviously, other factors (e.g., droughts, microclimatic conditions, soil nutrients) interfere with YB regeneration success but we were unable to identify them though we verified the effects of early seedling density, shrub competition, and herbivory among other factors. We conclude that (1) to ensure high YB regeneration, more intense monitoring is required (and probably other treatments such as vegetation control), and (2) if this monitoring is not possible, it may not be worthwhile to make efforts to favor YB establishment.

These two options can be implemented using a zoning strategy with contrasted-management intensities. In a context of climate change it is also worthwhile to question the idea of increasing YB in the landscape as it is susceptible to drought.

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Alternative Silviculture Treatments and the Influence on White-tailed Deer Behavior

M.D. Starking and G.J. Roloff¹

INTRODUCTION

Conflicts between herbivores and forest management vary depending on region and forest type. In northern hardwood forests of the north-central United States, high herbivore abundances, specifically white-tailed deer (*Odocoileus virginianus*), often cause problems by limiting tree stocking and regeneration of diverse tree species. Beginning in 2017, a collaboration between the Michigan Department of Natural Resources, Michigan State University, and forest industry partners began testing alternative silviculture in northern hardwood forest types across the state. Foresters and wildlife biologists developed a long-term, large-scale manipulative research project. We compartmentalized Michigan into three regions: eastern Upper Peninsula (EUP), northern Lower Peninsula (NLP), and western Upper Peninsula (WUP). We randomly assigned overstory (i.e., shelterwood, seed tree, larger group/patch cuts, and single tree/small group selection) and understory treatments (i.e., herbicide/scarification, and leaving treetops) to 12.14 ha forest stands (n = 140). A randomly chosen subset of these stands (n = 48) were used for detailed wildlife monitoring with a focus on white-tailed deer occupancy, residence time, and behavior such as movement. Questions we asked included (1) how does leaving piles of treetops (i.e., leave tops) as an understory treatment influence deer movement and browsing behavior, and (2) how well do these leave tops act as a barrier to herbivory. To promote regeneration of diverse northern hardwood species in areas with high-deer impacts, it is vital to understand the effects of silviculture methods on deer behavior and how interactions between forest management and wildlife management can work together toward sustainable ecosystem management.

METHODS

Deer movements were recorded through sites with leave top treatments December 2020 to March 2021 using snow-tracking surveys. A pair of observers would navigate the edge of the 12.14 ha treatment site until they walked the entire perimeter. If they encountered deer tracks in the snow, they would record a GPS track following the deer trail. Observers would follow the deer trail through the site until it was lost or until the deer exited the site. Along the route, observers collected depth of snow (cm) at the beginning, at any leave top encountered, and at the end of the trail. When a deer encountered a leave top, observers recorded the height (cm) of the tallest piece of wood if the deer traveled through the leave top or if the deer changed direction. A change in movement direction indicated a leave top successfully altered the movement path, potentially prohibiting deer from accessing browse within the leave top.

Generalized linear regression models with a negative binomial distribution predicted variables that influenced whether deer moved over or through leave tops or resulted in a change of direction. Variables included leave top height (cm), region (EUP, NLP, WUP), snow depth (cm), and overstory treatment. Because some sites were visited more than once, we included an offset

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in the model to account for number of visits to each site. We produced 10 candidate models and identified the top-ranking using Akaike information criterion (AIC). We deemed model parameter estimates with 95 percent confidence intervals that did not include 0 as significant.

RESULTS

Four different observers visited 26 leave top sites with an average of three visits per site over the winter of 2020–2021. Each observer recorded an average of three deer trails per site visit. Along recorded deer trails, observers recorded 546 leave tops encountered by deer. The average snow depth during site visits was 20 cm. Average leave top height was 68.9 cm with average deer movements going over or through tops that were ≤ 50 cm tall; taller tops served as barriers to movement and caused a change in movement direction.

Our top model included leave top height (cm), region, and snow depth (cm). Leave top height significantly affected deer movements, and this effect was different between the NLP and EUP. Snow depth was not significant. In the Upper Peninsula of Michigan (i.e., EUP and WUP), leave tops ≤ 50 cm tall have a ≥ 75 percent chance of deer going over or through them. Also in the Upper Peninsula, leave tops ≥ 100 cm tall have ≤ 25 percent chance of deer moving over or through them. In the northern Lower Peninsula leave tops needed to be ≤ 70 cm to have a 75 percent chance or greater for deer to move over or through them. Additionally, in the NLP, leave tops ≥ 120 cm had a ≤ 25 percent of deer moving through them. Thus, taller leave tops were needed in the NLP to deter deer movements, likely corresponding to areas with higher deer abundances compared to most sites we studied in the Upper Peninsula.

MANAGEMENT IMPLICATIONS

Our results show that structure of individual leave tops influence deer movements and as a result, leave tops may prove an effective strategy for deterring deer herbivory on regenerating trees. We found that tops with more volume (i.e., >50 cm tall but $<\sim 100$ cm tall) appeared to act as movement barriers. We recommend that leave tops be left intact, not be feller-bunched, and not be crushed by logging equipment to function as deer barriers. Additionally, we mapped the spatial distribution of leave tops across each site using drone imagery to understand how leave tops function across space. Preliminary results indicate that leave tops can be used to control deer movements at the site level, potentially funneling them away from tree regeneration areas like harvest gaps.

The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

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Preliminary Tree Regeneration and Browsing Patterns Following Various Silvicultural Treatments in Northern Hardwood Forests

Evan J. Farinosi and Michael B. Walters¹

INTRODUCTION

Many managed northern hardwood forests in northern Michigan contain low densities of desirable tree regeneration, while often simultaneously containing relatively high densities of undesirable tree species (e.g., *Fagus grandifolia* Ehrh., *Ostrya virginiana* Mill. K. Koch). Limited light availability that favors shade-tolerant species and a lack of viable germination substrate for many desirable tree species following harvest—as well as selective deer-browsing effects—likely contribute to this pattern. As a result, managers and researchers alike have been interested in testing alternative silvicultural practices that may achieve more sustainable regeneration layers. In 2017, a long-term, landscape-scale research project was established to examine how a wide range of silvicultural prescriptions (and site-level factors such as deer usage) may affect tree seedling regeneration and recruitment. Selective browsing patterns, particularly in the first few years following harvest, may play an outsized role in future tree species composition. While regeneration surveys are planned for 5 and 10 years post-treatment, earlier post-harvest surveys may elucidate patterns, particularly in browsing damage, that otherwise might have been missed. We set out to examine (1) early post-harvest stem counts and (2) interspecific deer-browsing intensity following four unique harvest types (also receiving one of two possible understory treatments) proposed for managed northern hardwood forests in Michigan. Understanding these browsing patterns may prove critical to the successful application of future harvests over a deer usage gradient.

METHODS

Data were collected on 140 30-acre research sites located in northern hardwood forests managed by the state of Michigan (~85 percent) or private industry (~15 percent) and were distributed throughout the northern Lower and Upper Peninsulas of Michigan. All sites were harvested between August 2017 and March 2018, with each site receiving one of four overstory treatments (i.e., seed tree, shelterwood, large-group selection/patch cut, or single-tree/small-group selection harvests). Mature, felled tree crowns were retained on half of the sites in order to test their effect on site-level deer usage. Seedling stem counts and data on browse availability/damage (i.e., total twigs/stem, plus total twigs browsed/stem) were collected (nine 50.24-m² plots per site) on trees >50 cm and <137 cm tall at each research site on 2-year-old seedling growth. This size class was chosen due to its importance in future stand composition and its current presence in the browsing zone. Pellet counts, a proxy for winter deer usage, were collected in early spring 2019 in linear transects that covered approximately 2 percent of each site.

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Generalized linear regression models with a negative binomial distribution were used to predict stem counts and total twigs browsed by species for the 15 most common species found in the study. Plot level data were aggregated to obtain a stand level estimate. Predictor variables for stem counts 2 years post-harvest included overstory treatment, understory treatment (i.e., mature felled tree crowns retained vs. removed), and preharvest stem counts (collected in 2017). Predictor variables for the total number of browsed twigs by species included overstory and understory treatments, as well as deer use (pellets/acre), available twigs of the species being modeled, and the sum of available twigs of generally palatable browse species.

RESULTS

Stem Count Results

Stem counts varied widely. Seed tree or shelterwood treatments contained higher stem counts than the single tree/small group selection treatment—the predominant silvicultural system used in this cover type—for 10 of 12 species that showed significant differences. Further, higher stem counts were found on sites in which mature, felled tree crowns had been retained following harvest (i.e., seven of eight species). Preharvest stem counts were a significant predictor for 13 of 15 species; unsurprisingly, shade intolerant *Populus* spp. and *Prunus pensylvanica* L. did not conform to this pattern.

Browsing Results

Interspecific browsing rates and browsing rate differences across silvicultural treatments were apparent. *Quercus rubra* L. experienced higher browsing rates following large-group selection/patch cut harvests, while *P. pensylvanica* experienced higher browsing rates following seed-tree harvests; both species experienced more browsing damage on sites where mature-felled tree crowns had been removed. Six species experienced increased browsing damage as deer usage estimates increased, including *Prunus serotina* Ehrh. and *Q. rubra*. *F. grandifolia* and *O. virginiana* were browsed less as the availability of palatable twigs increased.

Across the study, conifers such as *Picea glauca* (Moench) Voss, *Pinus strobus* L., and *Abies balsamifera* (L.) Mill, as well as the deciduous *F. grandifolia* were generally avoided; all experienced browsing rates under 6 percent. *O. virginiana*, *P. pensylvanica*, and *Q. rubra* twigs were browsed at rates less than 25 percent, while a large group of species were browsed at 30 to 35 percent, including *Acer rubrum* L., *P. serotina*, and *Acer saccharum* Marsh. *Betula alleghaniensis* Britton., *Tilia americana* L., and *Ulmus americana* L. were browsed at higher rates.

MANAGEMENT IMPLICATIONS

Preliminary results suggest the implementation of alternative silvicultural systems may lead to increased densities of many desirable tree species, particularly mid-tolerant species such as *B. alleghaniensis* and *Q. rubra*, as well as other desirable tolerant (e.g., *A. saccharum*) and intolerant (e.g., *P. serotina*) species. However, recruitment rates in the face of browsing damage and competing vegetation mean that further data collection and analysis will be necessary. While *P. strobus* was not generally abundant on study sites, it is a potentially beneficial structural component of future northern hardwood forests (particularly on drier sites) that does not seem to experience high levels of browsing. *A. saccharum*, the predominant economically valuable northern hardwood, experienced relatively moderate browsing intensity, along with many other hardwoods; it remains to be seen how these browsing rates will affect interspecific tree recruitment.

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Deer Browse, Pennsylvania Sedge, and Silviculture Strategies to Enhance Tree Regeneration

Colleen Matula, Paul Feine, and Emanuel Oradei¹

Abstract.—Complex interactions between heavy deer browse and plant response have resulted in structural and compositional changes in forest ecosystems. Sedge dominance and poor tree recruitment have been documented in northern hardwood stands across Wisconsin and Michigan. This study explores interactions of Pennsylvania sedge dominance and deer-browse impacts in northern hardwood forests with adaptive management strategies designed to enhance tree regeneration. We evaluated the immediate effects of several common silviculture site preparation techniques implemented in a recently harvested northern hardwood stand managed by Oneida County Forestry in Wisconsin. In 2004, we compared data characterizing this forest community before harvest and up to 15 growing seasons after implementation of the silvicultural treatments. Data collection included tree regeneration, herbaceous plants, and Pennsylvania sedge cover.

INTRODUCTION

Land use, deer management practices, mild winters, and other factors have contributed to unprecedented high deer densities in Wisconsin. Sustained deer browsing has significant negative impacts on forest herbs, tree recruitment, and forest vertical structure. However, there are some species that deer avoid, such as certain ferns, grasses and sedges, and some shrubs. The native Pennsylvania sedge (*Carex pennsylvanica*) has increased dramatically in some northern Wisconsin and Upper Michigan forest stands as deer browse pressure increases. The absence of northern hardwood regeneration with the dominance of Pennsylvania sedge is a growing concern among forestry professionals in Wisconsin.

Pennsylvania or yellow sedge is a native, low-growing, rhizomatous sedge occurring in clustered, persistent tufts. It is found in almost every state within the eastern United States. Pennsylvania sedge is readily found in northern Wisconsin and commonly present in northern hardwood understory. In some forest stands, it dominates the understory while hardwood regeneration and most other forest herbs are absent. There are very few studies on the complex interaction of sedge dominance, though some have documented possible causes including deer herbivory, exotic-earthworm invasion, and past forestry practices (Powers et al. 2009).

This study observes the silvicultural treatments used to control sedge dominance in an 80-acre northern hardwood stand in the Oneida County Forest. Past management history in this 90-year-old stand consisted of previous intermediate harvest treatments. The terrain is rolling moraine with sandy loam soils. The stand composition is predominately sugar maple (*Acer saccharum*), basswood (*Tilia americana*), white ash (*Fraxinus americana*), and northern red oak (*Quercus rubra*) with some hemlock (*Tsuga canadensis*), balsam fir (*Abies balsamea*), white pine (*Pinus strobus*), white birch (*Betula papyrifera*), and aspen (*Populus* spp.). There are two to three size classes and average tree diameter is approximately 15 inches with pole timber and very few tree

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seedling, saplings, and understory herbs. Pennsylvania sedge was the dominant understory vegetation. During winter of 2004–2005, an even-aged thinning with gaps was implemented leaving a residual basal area of 90 square feet and included 60-foot canopy gaps, one per acre throughout the stand. In early summer 2005, a variety of site preparation treatments were conducted in the gaps. Approximately 10 or more gaps per treatment were selected. Herbicide treatment was implemented using a variety of herbicide combinations to control the sedge (i.e., Oust® [Bayer Environmental Science], Velpar® [Bayer Environmental Science], Diuron [Alligare], and Plateau® [BASF]). The prescribed fire treatment was attempted in early spring but the sedge's resistance to ignition made burning difficult. Blade scarification was implemented in the gaps with a bulldozer. The ground was carefully scraped to set back the sedge mat and expose mineral soil. The last treatment was a combination of blade scarification and herbicide in the gaps. Five deer exclosures were also established by installing an 8-foot plastic fence placed along the periphery of each 60-foot gap, one per treatment.

The sedge cover was evaluated in each gap before and after treatment. Sedge cover was estimated on each plot per treatment and assigned a value from 0 to 4 (i.e., 0 = no sedge cover; 1 <25 percent cover; 2 = 25 to 50 percent cover; 3 = 51 to 75 percent cover; 4 = 76 to 100 percent cover). These results were assessed for the adequacy of the treatment. In this study, we observed that a sedge cover rating of 50 percent or more is significant coverage, eventually dominating the site. All plots had 75 percent or more sedge cover before treatment.

Tree regeneration data were collected in each gap to assess the species and adequacy of established regeneration. Erdmann's recommendation (i.e., having a minimum of 2,000 to 5,000 seedlings per acre where above 3 feet tall; Erdmann 1986) was used to gauge regeneration adequacy in this project.

RESULTS

The results in this report represent vegetation response after harvest and site preparation treatments monitored from 2005–2021.

Sedge Cover

The herbicide and herbicide/scarification treatments were the most successful by initially reducing the sedge to less than 50 percent cover. Although several herbicide combinations were tested, the herbicide Oust XP (1 oz/acre) was the most successful at reducing the sedge mat. The prescribed burning treatment was not successful since the sedge is somewhat fire resistant. The blade scarification treatment was not successful since it was difficult to break up the sedge mat. When we returned to the site in 2021 (15 years after the treatment) all sedge cover had returned to >75 percent throughout the stand.

Tree Regeneration

The results indicate that over half of herbicide and herbicide/scarification treatment plots initially had good to very good regeneration (>2,000 stem/acre). More white ash (*Fraxinus americana*) stems established on the control plot and more sugar maple (*Acer saccharum*) on the herbicide plots. By spring of 2010, most established regeneration in the plots surpassed browse height of 5 feet. However, the 2021 inventory data indicated lower stocking densities across all treatments (Fig. 1). Deer herbivory on seedlings and saplings was evident.

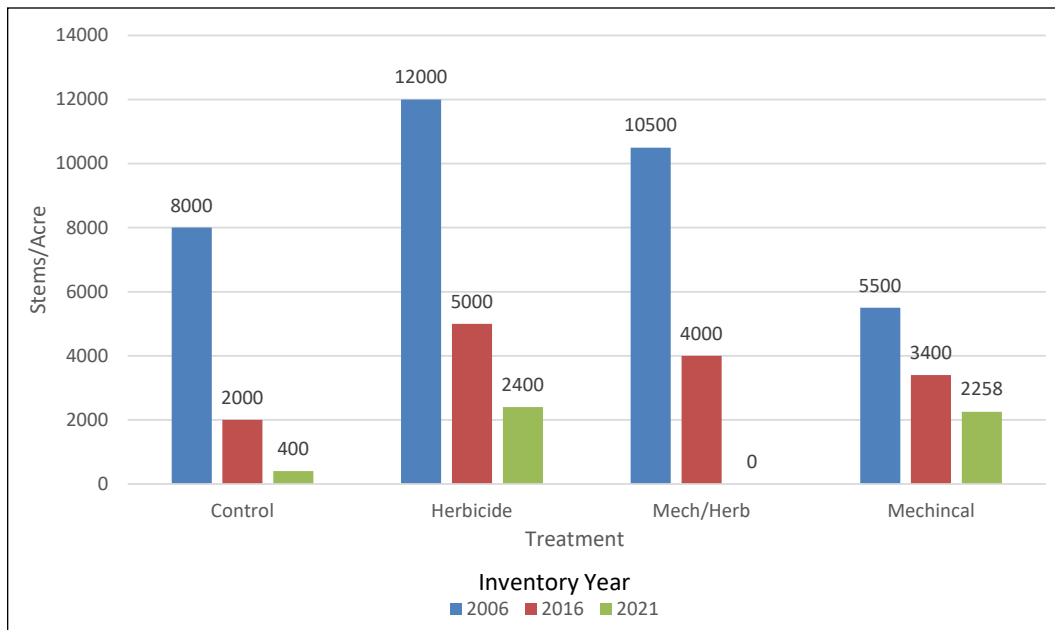


Figure 1.—Tree regeneration by treatment and year.

Deer Exlosures

Each of the five deer exclosures represented a different treatment including control, fire, herbicide, blade scarified, and no treatment/no harvested canopy gap. The herbicide treatment was most successful at reducing the sedge and had the most seedlings (i.e., 18,000 seedlings per acre). All fenced treatments had more than adequate regeneration (i.e., >5,000 seedlings per acre). The herbicide treatment had predominantly sugar maple and white ash seedlings. The blade scarification treatment had abundant white birch (*Betula papyrifera*) seedlings, however, many weedy species such as raspberry, mullein, and thistle were present. By 2010, seedling height in all fenced areas ranged from 5 to 8 feet for sugar maple and white ash. In the area that was not fenced, tree seedlings remained 1 to 2 feet high and were heavily browsed. By 2015, fences were removed, and most saplings previously fenced exceeded 20 feet high. When we returned in 2021, the established tree regeneration in the gaps surpassed browse height but surrounding vegetation was browsed.

DISCUSSION

Our results in this project suggest an interaction between deer herbivory contributing to a reduction in tree regeneration. Two years after harvest, tree regeneration in the fenced gaps was abundant and successfully grew through the sedge. This observation suggests deer browse is a significant factor in reducing tree regeneration, understory herbs, and indirectly allows sedge dominance. Under high browse, deer can exclude understory vegetation while some species such as ironwood and sedge flourish.

Though observation continues, our results suggest that the herbicide treatment was effective at hastening sedge in the short term while allowing the establishment of tree regeneration. One recommendation is to apply a fall herbicide application to minimize mortality of understory plants and optimize plant diversity. Broad-scale application of herbicide might be logistically and economically difficult. Instead, small patch treatment would allow opportunity for regeneration to establish a good tree-seed crop.

Ensuring adequate levels of regeneration in northern hardwood forests may require development of strategies that address complex interacting factors. Adopting silviculture systems that consider thorough site assessments, structural considerations, limiting deer densities, and reducing Pennsylvania sedge may be necessary to meet management objectives. More experimental silviculture trials are needed to determine how these factors continue to alter structural and compositional changes in northern hardwood forest ecosystems.

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Forest Vegetation Management: A Matrix of Options

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Forest understory vegetation complexes that interfere with management objectives can consist of native and nonnative species ranging from annual herbs to long-lived woody species. Each species presents different challenges if they have reached a threshold that warrants a management response to restore and maintain habitat, ecological function, productive potential, and other values commonly associated with woodlands.

In 2016, a team of foresters from Cornell Cooperative Extension started a 3-year National Institute of Food and Agriculture (NIFA)-funded project known as Forest Vegetation Management (FVM) to evaluate and develop recommendations for forest managers in the northeastern United States. An outcome of those efforts is shown in the Table 1 matrix. The matrix allows managers to rapidly assess options for similar types of shade-tolerant plants², then focus on methods likely to yield desirable results for each context.

Every plant has at least one control method. No single method works well across all types of plants or for all configurations of ownership and management. Consequently, developing a sound strategy starts with identifying ownership objectives and constraints with the targeted vegetation types (Table 2) then selecting one or more appropriate methods (i.e., those rated as a 1 or 2, as defined in Table 3) from the matrix.

Detailed guidance for each method is captured in Table 4. The guidance was developed into an extension bulletin of the same name (available at <https://bit.ly/2ZuHB4r-FVM-Matrix>) and on the Cornell Cooperative Extension forestry extension website at www.ForestConnect.info. This information was compiled primarily through two methods: the results of applied research projects on aspects of forest vegetation management conducted mainly at the Cornell University Arnot Teaching and Research Forest, and interviews with forestry professionals that were part of the FVM project.

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² Local regulations may restrict some options.

Table 1.—Matrix FVM options. For the description of vegetation growth form, see Table 2. For the description of number codes, see Table 3. For the description of treatments (chemical, mechanical, etc.), see Table 4.

Vegetation Growth Form	Chemical		Mechanical			Integrated	Biological
	Foliar (broadcast or individual)	Basal/injection (individual)	Mow/cut (broadcast or individual)	Girdle (individual)	Excavate (broadcast or individual)	Cut-stump, cut-surface, or cut-stubble	Silvopasture/ livestock impact
Herbaceous, short-lived	2	3	2	3	3	3	2
Low herbaceous, perennial	1	3	2	3	3	2/3	2
Tall herbaceous, perennial	1/2	3	2	3	3	2	2
Vines, annual	1	3	2	3	3	3	2
Vines, perennial	2	3	2	3	3	1	2
Canes	1	3	1	3	2	1	2
Shrubs	2	2	1	2	1	1	2/3
Trees	2/3	1	1	1	2	1	2/3

Table 2.—Examples of vegetation growth form in the FVM matrix

Plant Type	Example
Herbaceous, short-lived	Stiltgrass, garlic mustard
Low herbaceous, perennial	Ferns, grasses
Tall herbaceous, perennial	Knotweed, swallow wort
Vines, annual	Mile-a-minute
Vines, perennial	Grape, bittersweet, poison ivy
Canes	Rubus, multiflora rose
Shrubs (<10 inches)	Barberry, autumn olive, honeysuckle, privet, euonymus, buckthorn
Trees (>10 inches)	Beech, carpinus, ostrya, striped maple, tree-of-heaven

Table 3.—FVM matrix codes

Code	Description
1	Good results While correct protocol is important, control of the target is high and generally robust in effectiveness.
2	Mixed results These treatments can be applied successfully, but attention to protocols is important. Without this attention, success is unlikely.
3	Impractical to implement or insufficient results There is limited research or experience for this treatment, or—while the treatment is theoretically possible—it is unlikely to succeed due to logistical or practical constraints.

Table 4.—Explanations for predicted outcomes

Chemical—foliar	Selective, nonselective, and pre-emergent herbicides for labeled use can be partially effective when applied under the right conditions. Factors limiting effectiveness in forest applications include: access; coverage; plant conditions like growth phase and drought stress; resistance features, both genetic and morphological; meteorological conditions; and skilled application. Broadcast herbicide treatments are usually more effective for short-term control—such as to temporarily reduce understory interference to establish or release regeneration—and are most effective when coupled with other control strategies.
Chemical—basal or injection	Basal spray and injection are impractical treatment methods for most types of interfering vegetation, larger woody stems that are readily accessible. Basal treatment formulations will be most effective on thin-barked species like beech. Systemic herbicides labeled for injection will yield the best results when wood is not frozen and the proper dosage is used according to the product label.
Mechanical—mow or cut	Severing stems by cutting either with simple tools or specialized machines provides instant gratification, but usually short-lived results. Most example plants are capable of vigorously resprouting. Intensive and continued mowing would be necessary to exhaust root reserves to mortality for most species. Nonetheless, judicious mowing can increase the viability of more durable methods from the chemical and biological categories.
Mechanical—girdle	Girdling is impractical except for larger-diameter woody stems that are unlikely to sucker or coppice. The cambium tissue beneath the bark must be fully severed and some species can take several years to die.
Mechanical—excavate	Plants and most roots are removed using heavy equipment. This is effective for species that will not propagate from root fragments. However, the significant soil disturbance associated with excavation will often stimulate the soil seed bank and potentially give rise to other noxious plant problems.
Integrated	Mechanical cutting followed by immediate chemical treatment of the fresh stumps can enhance the effectiveness of control for plants where the cut surface is sufficiently large to absorb the labeled herbicide treatment.
Biological—silvopasturing	Managed livestock impacts such as defoliation, girdling, browsing, and trampling are used to limit the growth of undesirable plant species while fostering the growth of desirable ones. Silvopasture establishment usually requires some combination of initial treatments from other vegetation management options to reduce vegetation height and density before livestock can be effective. Targeted livestock impacts through intensive rotational grazing will gradually shift understory vegetation to a more stable complex resistant to invading plants.

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STAND DYNAMICS

Long-Term Evolution of Composition and Structure After Repeated Group Selection: 80 Year Results

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INTRODUCTION

Selection systems have a long history of application across a range of forest types as a means for sustained yield and preserving diverse forest structure (O'Hara 2002). In the northeastern United States, group selection is a commonly used method for management of northern hardwood forests (Leak et al. 2014). This approach is well regarded for maintaining uneven-aged stand attributes as well as retaining a range of shade tolerant and intolerant species. However, forest characteristics following management with group selection are primarily assessed at the stand level. This approach leaves uncertainty about ecological developments at the cohort level as well as the cumulative influence of each cohort over time.

STUDY SITE

To further explore these knowledge gaps, we examined a long-term group selection study at the Bartlett Experimental Forest in New Hampshire (Rogers et al. 2020). The Bartlett Experimental Forest is home to one of the longest running group selection treatments in North America with repeated application over eight decades. The duration of this study provided a unique opportunity to evaluate structural and compositional evolution at the stand and cohort level. Specifically, we assessed the stand-level diameter distribution and overstory composition relative to individual cohorts.

RESULTS AND DISCUSSION

Results highlight cohorts developing as small even-aged stands that collectively create an uneven-aged condition at the stand level. For example, the overstory stand diameter distribution follows rotated sigmoid curve, a shape seen in other uneven-aged northern hardwood forests (Fig. 1). The stand distribution shape was largely influenced by the number of small stems in the 1993 cohort as well as the number of large trees in the 1938 and matrix cohorts. Overstory trees are those 11.43 cm at breast height or greater. Stand structure is also the result of mortality and successional dynamics within each cohort. The elevated levels of pin cherry (*Prunus pensylvanica*) downed woody material ($\text{m}^3 \text{ha}^{-1}$) in the 1960 cohort and paper birch (*Betula papyrifera*) downed woody material in the 1960 and 1951 cohorts reflect the ecological properties of these species, specifically, their short life span relative to other northern hardwood species (Burns and Honkala 1990). The amount of American beech (*Fagus grandifolia*) downed woody material across cohorts is the byproduct of beech bark disease. The disease complex, part necrotic canker (*Neonectria* spp.), part scale insect (*Cryptococcus fagisuga*), has been present in the region since the early 1900s (Houston 1975). As mature American beech succumb to the disease, overstory trees are replaced by dense thickets of root suckers increasing overall composition of American beech relative to

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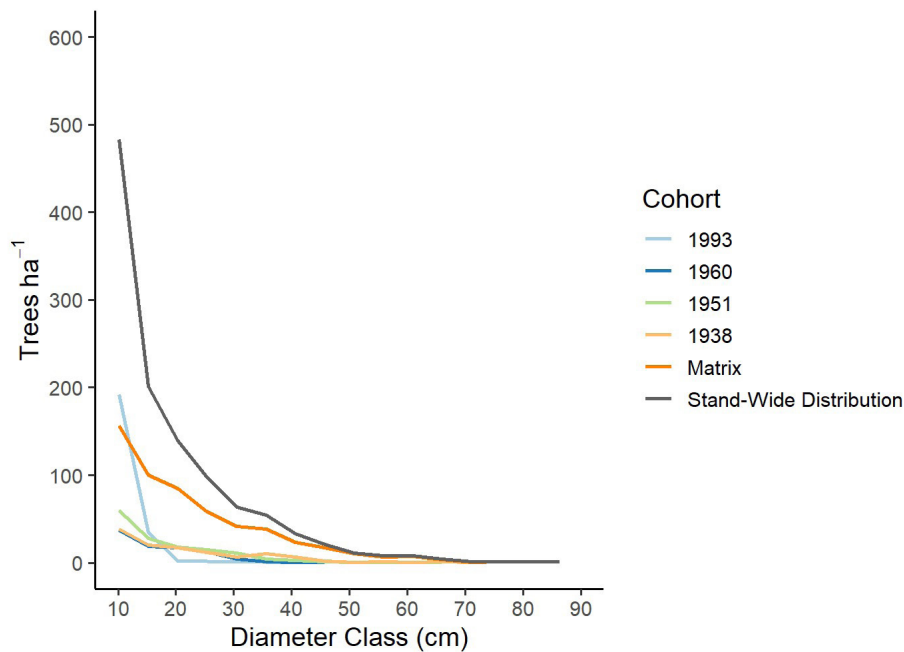


Figure 1.—Overstory diameter distribution (tree ha⁻¹), cohort-level, and cumulative stand outcomes.

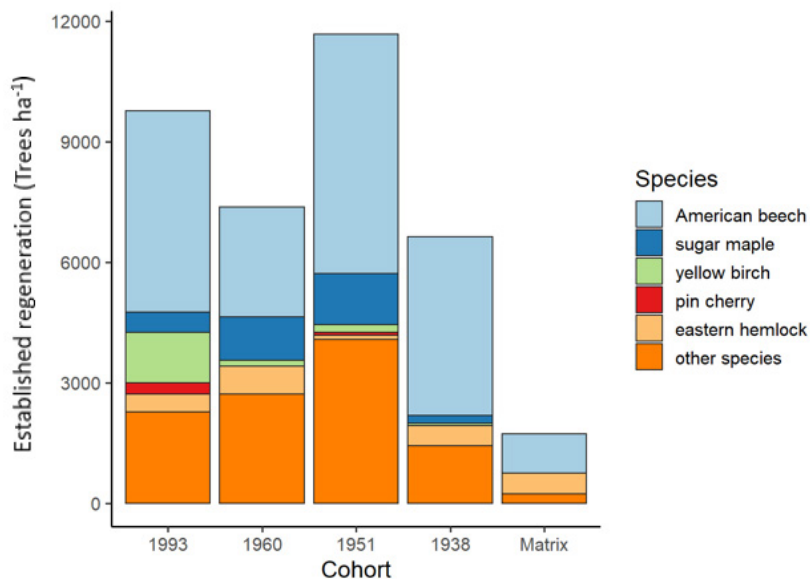


Figure 2.—Density of established regeneration (trees ha⁻¹) by species and cohort.

other more commercially desirable species like sugar maple (*Acer saccharum*) and yellow birch (*Betula alleghaniensis*). Dominance of American beech is especially likely, and problematic, on moderate to poor sites, including those at the Bartlett Experimental Forest. A benefit of group selection on such sites is the maintenance of species with a wide range of shade tolerances (Leak et al. 2014). The cumulative stand includes more shade tolerant species, such as eastern hemlock (*Tsuga canadensis*) and American beech, but also intolerant and mid-tolerant species. Species diversity is also seen in the regeneration layer following each harvest (Fig. 2). Although American beech is still dominant in this smaller size class, sugar maple and yellow birch regeneration are present in all cohorts excluding the matrix. These findings suggest group selection maintains diverse regeneration even on a moderate site. Over time, cohort development mirrored

successional dynamics associated with even-aged forest systems while stand-scale attributes reflected conditions anticipated in uneven-aged systems. These long-term results offer important knowledge about processes that may impact recruitment of desirable regeneration. Further, these findings provide important details on emergent cohort and stand-level conditions for forests managed using this approach over numerous cutting cycles.

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Five-year Growth Response of a 41-year-old Yellow Birch Stand to Commercial Thinning

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Abstract.—Yellow birch (*Betula alleghaniensis* Britt.) is the second most harvested hardwood species in Quebec. Hardwood stands harboring this species are likely to yield high value products, and their proximity to inhabited regions facilitates a more intensive silviculture. Yet, little is known about the effects of silvicultural treatments such as commercial thinning on stands composed mostly of yellow birch. We set up an experiment in a 41-year-old yellow birch stand that arose after a clearcutting in 1971. The experimental design comprises four treatments: a control (no intervention); and light, moderate, and heavy commercial thinnings. After 5 years, results show that the thinnings had no significant effect on the net growth in basal areal of the stand. The treatments mostly led to an increase in the proportion of yellow birch and crop trees in the stand following the harvest targeting aspens and other less desired species. The smaller diameter trees near the trails showed the highest diameter growth response to the thinnings.

INTRODUCTION

Yellow birch (*Betula alleghaniensis* Britt.) is the second most harvested hardwood species in Quebec. The market value of its premium quality lumber is excellent (CRIQ 2002). In the past, selective harvesting aimed at removing the most valuable trees, as well as difficulties related to its regeneration, have led to a decrease in the abundance of quality yellow birch trees (Boulet 2015). The proximity of yellow birch stands to inhabited regions and sawmills offers the opportunity to practice a more intensive silviculture in these stands.

Previous work from Robitaille et al. (1990) has shown that clearcutting in a sugar maple (*Acer saccharum* Marsh.)-yellow birch stand can promote the return of yellow birch when accompanied by sufficient soil disturbance. This work also confirmed that precommercial thinning provides an advantage for yellow birch over competing species by having a marked increasing effect on sapling diameter growth. Similarly, in order to promote the growth of better quality trees and allow them to reach more rapidly the diameter necessary for the production of high value lumber, commercial thinning (referred hereafter as thinning), may be an appropriate treatment. Commercial thinning is an intermediate partial cutting conducted in even-aged stands when a portion of the stems has reached a relative commercial maturity. The reduction of stand density allows growing space and resources to be reallocated to remaining trees (Laflèche et al. 2013, Nyland 2002). In hardwood stands, the main objective is to promote the growth of better quality trees so that they reach their financial maturity diameter (45 cm; Guillemette 2016) more rapidly.

Yet, little is known about the effects of silvicultural treatments such as commercial thinning on stands composed mostly of yellow birch. Since their abundance is limited, very few studies have empirically investigated the quantitative effects of mechanized thinning in even-aged yellow birch stands that are approximately 40 years old and to our knowledge, none has been conducted in a similar site. A more intensive, even-aged silvicultural regime is however likely to allow the

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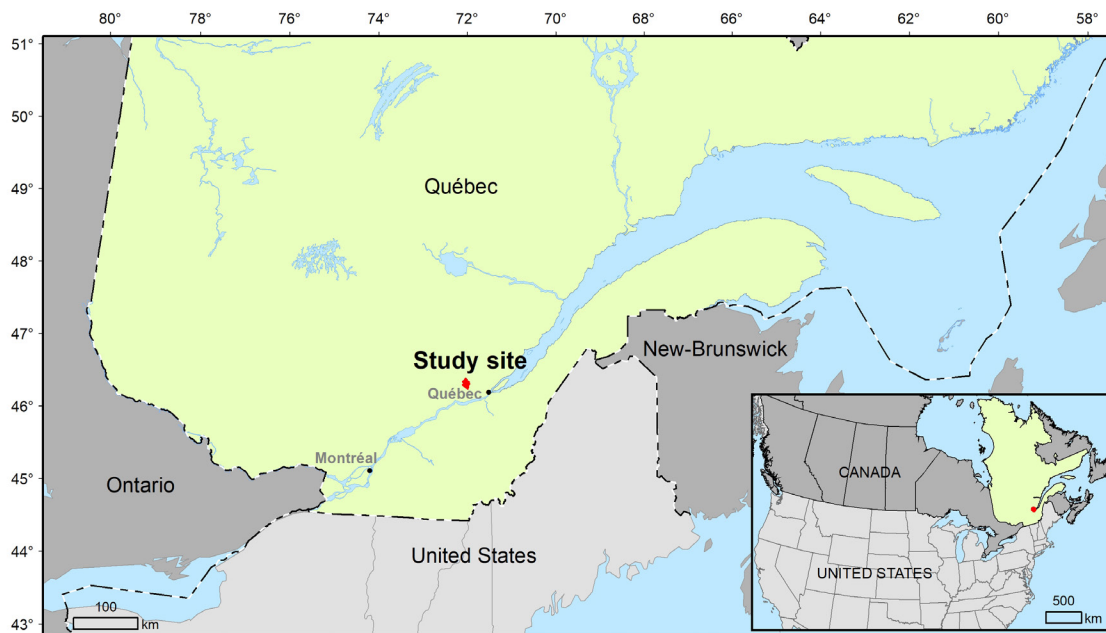


Figure 1.—Location of the study site.

production high quality and high valued lumber. The objective of this study was therefore to determine the effects of commercial thinning on basal area (BA) increment of crop trees and stand-level production in a 40-year-old yellow birch stand.

MATERIALS AND METHODS

Study Site

The experimental site is located 40 km northwest of Quebec City, Canada (lat. 46° 52' N., long. 71° 39' W.; Fig. 1). This area is in the southernmost ecological region of the eastern balsam fir-yellow birch bioclimatic subdomain (Saucier et al. 1998). Stands of balsam fir (*Abies balsamea* L.) and yellow birch are the most frequently encountered. However, the region benefits from a relatively mild climate; the long and regular slopes are colonized by maple stands, in which the main companion species are yellow birch and American beech (*Fagus grandifolia* Ehrh.). The mean annual temperature is 2.5 °C and the mean annual precipitation is approximately 1,200 mm (Blouin and Berger 2003).

The 24-ha site was established in 2012 in a yellow birch stand that arose after a clearcutting in 1971. In the past, the site has hosted an experimental setup established to monitor the effects of a precommercial thinning conducted in 1981 (Robitaille et al. 1990). The potential effect of this earlier experiment in the present study was isolated through the experimental blocks. Thus, all treatments in the same experimental block in the 2012 setup had received the same precommercial thinning treatment in 1981. The current setup includes seven complete blocks each comprising four square or rectangular-shaped experimental units, having an area of 1000 m² (0.1 ha). Before treatment, between 46.3 and 63.7 percent of the unit's BA was occupied by yellow birch, while quaking aspen (*Populus tremuloides*) accounted for 16.5 to 31.2 percent of the BA (Table 1). The quadratic mean diameter was 16.6 cm.

Table 1.—Average dendrometric characteristics and species composition by treatment and time of survey: merchantable basal area (BA) and stand density, quadratic mean d.b.h. (QMD) and species abundance

Treatment	Survey	BA (m ² ·ha ⁻¹)	Density (trees·ha ⁻¹)	QMD (cm)	Species* (% of BA)				
					YB	SM	QA	Other	NCOM
Control	Before	21.2	1,077	16.6	57.2	3.2	21.1	9.9	8.7
	After	21.2	1,079	16.6	57.1	3.2	21.2	9.8	8.6
	5 years	23.2	1,009	18	62.8	3.7	20.6	10.1	2.8
Light thinning	Before	22	1,104	16.6	63.7	4.9	16.5	8.1	6.7
	After	14.4	713	16.8	68.9	5.4	12	9.3	4.3
	5 years	16.8	721	17.9	72.7	6.1	10.8	9.1	1.2
Moderate thinning	Before	22.7	1,130	16.7	58.2	3.4	25.2	6.9	6.3
	After	11.9	593	16.9	71.4	3.8	14.9	6.4	3.6
	5 years	14.6	653	17.7	77.3	4.7	11	5.6	1.4
Heavy thinning	Before	22	1,099	16.6	46.3	7.4	31.2	8.5	6.6
	After	9.6	499	16.5	66.4	9.4	14.6	7.7	1.9
	5 years	12.3	557	17.5	70.1	10.5	10.3	8.5	0.6

*YB = yellow birch, SM = sugar maple, QA = quaking aspen, Other = other commercial species, NCOM = Noncommercial hardwood species.

Four treatments—that is a heavy thinning, a moderate thinning, a light thinning, and a control—were randomly assigned among the experimental units of each block. The heavy thinning targeted a residual BA of 8.8 m²·ha⁻¹, while the target residual BA for the moderate and light thinnings was 12.5 m²·ha⁻¹ and 15.4 m²·ha⁻¹, respectively. These residual BA targets for the heavy and light thinnings corresponded respectively to the minimum density threshold that should be maintained in a stand (C-line) and the optimal density to promote overstory growth (B-line), according to the density management diagram of Leak et al. (2014). The moderate intensity treatment represents an intermediate situation.

Data Collection, Marking and Harvest Operations

Measurements were carried out before cutting (summer 2012), after cutting (fall 2012), and 5 years after cutting (fall 2017). For all trees with a diameter at breast height (d.b.h.) of 91 mm or greater, we recorded the species, tree health condition, d.b.h. and canopy position class. Among trees of the desired species, yellow birch, paper birch (*Betula papyrifera* Marsh.), sugar maple, red spruce (*Picea rubens* Sarg.), and white spruce (*Picea glauca* (Moench) Voss), crop trees were identified based on criteria related to the social status, vigor class, branching structure, and quality. Crop trees to be retained were marked, including in the control units, to allow comparing the increment of marked and nonmarked trees. Crop trees were chosen considering an average spacing of 8, 10, or 14 m depending on the targeted residual BA. An average spacing of 10 m was used for the control plots. The density of marked trees was 194, 144, and 64 trees·ha⁻¹ for the heavy, moderate and light thinning treatments respectively, and 129 trees·ha⁻¹ for control. Harvesting was carried out through the cut-to-length harvesting system, using a harvester with a processing head and a forwarder for the skidding of the 2.5 m long logs (Fig. 2). The harvesting guidelines comprised the establishment of 4.5 m trails 20 m apart, and the harvesting of the two largest competitors of each marked trees. Harvest of aspen trees was indirectly prioritized since this species was not one of the desired species and aspen stems were often larger than that of other species. Therefore, in some cases, the harvesting of the larger aspen trees resulted in thinning the stand from above.



Figure 2.—Machinery used for harvesting: (a) harvester with a processing head; (b) forwarder. Courtesy photo by François Guillemette/MFFP, used with permission.

Data Processing and Statistical Analysis

BA ($\text{m}^2 \cdot \text{ha}^{-1}$) data were summed at the stand level according to the components of periodic annual increment, as proposed by Erdmann and Oberg (1973), that is the survivor growth, ingrowth, mortality, gross growth and net growth. Increments were calculated from the d.b.h. measurements.

To investigate the presence of a significant effect of the treatments ($p < 0.05$), we performed analyses of variance on the stand-level components of periodic annual increment in BA. Analyses were also conducted to investigate the effect of the treatments on the diameter increment at the tree level. The treatment was specified as a fixed effect. The block was considered as a random effect in the case of stand-level analyses, whereas for tree-level analyses, the experimental unit was considered as a random effect. The analyses were performed using packages *lme4* (Bates et al. 2015) and *emmeans* (Lenth et al. 2018) in the R programming environment (version 3.5.1, R Core Team 2018).

We divided the trees into three d.b.h. classes (10–12 cm, 14–16 cm, 18 cm and greater) in order to assess the effect of treatment on diameter growth. These classes were chosen in order to divide the population in groups of similar size. When a significant effect of one of the explanatory variables was detected, multiple comparisons were conducted using Tukey's test. The postulates of homogeneity of variance and normality of residuals were verified visually. Only one variable, ingrowth, required a logarithmic transformation. For this variable, we performed the analysis of variance as well as the multiple comparisons using the transformed variable, but we present the results using the untransformed data as for all other variables.

RESULTS

Pre- and Post-Harvest Stand Characteristics

Prior to harvesting, mean merchantable BA ranged from 21.2 to 22.7 $\text{m}^2 \cdot \text{ha}^{-1}$ depending on treatment (Table 1). The mean basal area removed was 7.6 $\text{m}^2 \cdot \text{ha}^{-1}$, 10.8 $\text{m}^2 \cdot \text{ha}^{-1}$, and 12.4 $\text{m}^2 \cdot \text{ha}^{-1}$, respectively, for the light, moderate, and heavy thinnings. BA after thinning was 14.4 $\text{m}^2 \cdot \text{ha}^{-1}$, 11.9 $\text{m}^2 \cdot \text{ha}^{-1}$, and 9.6 $\text{m}^2 \cdot \text{ha}^{-1}$, respectively, for the three thinning intensities. The achieved residual BAs were similar to that targeted, although a little lower than expected for the light thinning and a little higher than expected for the heavy thinning. In the lightly thinned experimental units, mean density was reduced by 35 percent, while it was reduced by 47 percent in the moderate intensity

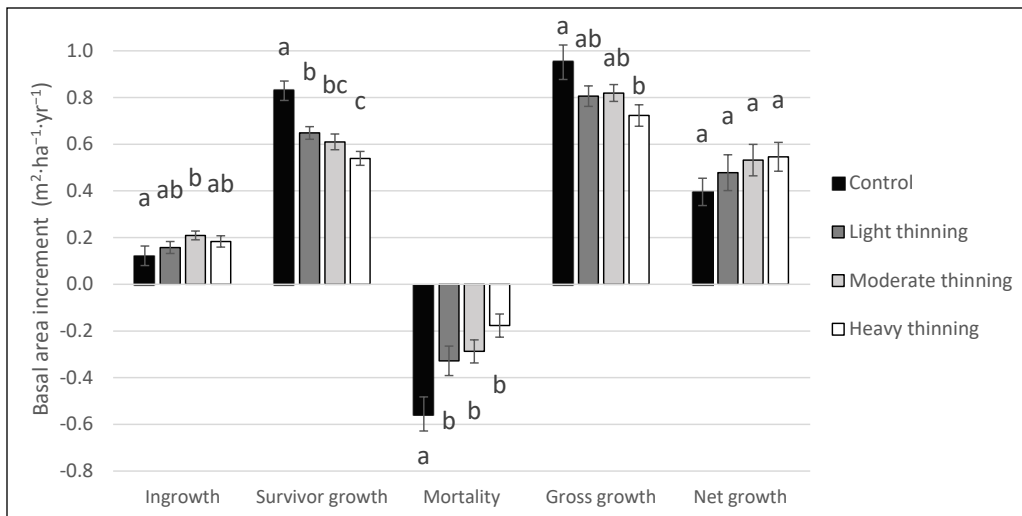


Figure 3.—Basal area increment for the first 5-year period after harvesting, by treatment. Error bars correspond to the standard error. Differing letters indicate significant differences among treatments.

thinning and by 55 percent in the heavy thinning (Table 1). The quadratic mean diameters were similar in all treatments, before and after thinning, ranging from 16.5 to 16.9 cm.

Treatments resulted in an immediate increase of 5.2 to 20.1 percentage points in the proportion of BA occupied by yellow birch, which averaged 66.4 to 71.4 percent of total merchantable BA after treatment. Five years later, yellow birch accounted for 70.1 to 77.3 percent of BA in thinned units, but only 62.8 percent in control units. Priority harvesting of trembling aspen, reaching 15 to 33 $\text{m}^3 \cdot \text{ha}^{-1}$, considerably reduced its presence in treated units. Whereas this species occupied 16.5 to 31.2 percent of the BA before treatment, it represented only 10.3 to 11 percent of the total merchantable BA 5 years after treatment, whereas it still occupied 20.6 percent of the BA in the control plots. Noncommercial hardwoods, represented mainly by pin cherry (*Prunus pensylvanica* L. f.), occupied 6.3 to 8.7 percent of the BA before cutting. However, the presence of these species had significantly decreased 5 years after treatment (from 0.6 to 2.8 percent of BA), including in the control units.

Stand-level Growth

Net BA growth only varied slightly between treatments, reaching 0.48 to 0.55 $\text{m}^2 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ in the treated plots, and 0.40 $\text{m}^2 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ in the control (Fig. 3). An examination of the components of stand growth provides insight into the effect of treatments on growth dynamics in the experimental units. For instance, survivor growth was significantly different among treatments ($p < 0.001$; Table 2) and was greater for control than thinned units ($p < 0.001$). Among treated plots, the survivor growth was greater in the low intensity treatment than in the heavy thinning treatment

Table 2.—Results of analyses of variance on the effect of treatments on the components of five-year periodic increment in basal area. P-values indicating a significant effect are shown in bold.

Variable	DF num*	DF den*	F-test values	p-values
Net growth	3	18	2.19	0.125
Survivor growth	3	18	30.1	<0.001
Ingrowth	3	18	3.47	0.038
Gross growth	3	18	4.47	0.016
Mortality	3	18	7.24	0.002

*DF num = numerator degrees of freedom; DF den = denominator degrees of freedom

Table 3.—Annual increment in diameter for each treatment, by species and d.b.h. class

Species	d.b.h class	d.b.h. annual increment (mean $\pm$ standard error, mm·yr ⁻¹)			
		Control	Light	Moderate	Heavy
Yellow birch	10-12 cm	2.0 $\pm$ 0.1	3.2 $\pm$ 0.2	3.3 $\pm$ 0.2	4.2 $\pm$ 0.3
	14-16 cm	3.3 $\pm$ 0.1	4.0 $\pm$ 0.2	4.5 $\pm$ 0.2	4.8 $\pm$ 0.4
	18+ cm	5.0 $\pm$ 0.2	5.1 $\pm$ 0.2	5.5 $\pm$ 0.2	5.8 $\pm$ 0.2
All species	10-12 cm	1.9 $\pm$ 0.1	3.1 $\pm$ 0.2	3.2 $\pm$ 0.2	3.8 $\pm$ 0.2
	14-16 cm	3.1 $\pm$ 0.1	3.6 $\pm$ 0.2	4.2 $\pm$ 0.2	4.4 $\pm$ 0.3
	18+ cm	4.4 $\pm$ 0.2	4.8 $\pm$ 0.2	5.2 $\pm$ 0.2	5.4 $\pm$ 0.2
	All	3.1 $\pm$ 0.1	3.8 $\pm$ 0.1	4.2 $\pm$ 0.1	4.5 $\pm$ 0.1
Marked	All	4.6 $\pm$ 0.2	5.7 $\pm$ 0.3	5.3 $\pm$ 0.2	5.6 $\pm$ 0.2
Nonmarked	All	2.9 $\pm$ 0.1	3.4 $\pm$ 0.1	3.8 $\pm$ 0.1	3.6 $\pm$ 0.2

($p = 0.033$). The ingrowth also varied by treatment ($p = 0.038$), but in the opposite direction than survivor growth; it was greater in treated units than in the control, although multiple comparisons revealed a significant difference only between the moderate thinning and the control ($p = 0.033$). Gross growth, the sum of survivor growth and ingrowth, varied by treatment ($p = 0.016$; Table 2) and was significantly greater in the control than in the heavy thinning ($p = 0.005$), with a difference of 0.23 m²·ha⁻¹·year⁻¹ (Fig. 3). Finally, mortality also varied significantly between treatment ($p = 0.002$; Table 2). Mortality was significantly higher in the control than in the heavily ($p = 0.001$) and moderately thinned ($p = 0.023$) units, but that was not true for the light thinning ($p = 0.061$).

Tree-level Growth

The effect of thinning on diameter growth of residual trees depended on the thinning treatment as well as the d.b.h. of residual trees. Compared to the control, thinning increased diameter growth of residual trees only for trees in the d.b.h. classes 10 to 12 cm and 14 to 16 cm in the heavy thinning treatment ($p < 0.05$).

Tree diameter increment was different ($p < 0.05$) among the d.b.h. classes for all treatments but the 10 to 12 cm and 14 to 16 cm d.b.h. trees in the heavy thinning ($p = 0.051$). There was no significant effect of the treatment on the growth of trees with a d.b.h. of 18 cm and above ($p = 0.112$), which showed a mean increment of 4.8 $\pm$ 0.1 mm·year⁻¹ (Table 3). The diameter increments of trees in the 10 to 12 cm and 14 to 16 cm d.b.h. classes were significantly different ($p \leq 0.023$) whether they were located in the heavy thinned units (3.8 $\pm$ 0.2 mm·yr⁻¹ and 4.4 $\pm$ 0.3 mm·yr⁻¹) or in the control (1.9 $\pm$ 0.1 mm·yr⁻¹ and 3.1 $\pm$ 0.1 mm·yr⁻¹). The conclusions of the statistical tests were the same whether we considered only yellow birch or trees from all species.

DISCUSSION

Influence of Thinning Intensity on Stand Level Net Growth

The net growth measured in the thinned experimental units was not significantly different from that measured in the control units. Compared to the control, the heavy and moderate thinning treatments resulted in reduced mortality ($p < 0.05$), while the moderate thinning also increased ingrowth ($p < 0.05$). These effects combined with the increase in diameter growth of the residual trees compensated for the reduced number of trees in the thinned stands. Although these results

suggest that greater cumulative yields will indeed be achieved in the thinned units by the end of the rotation (Nyland 2002), they contrast with findings of other studies that also concluded to a significant increase in net growth consecutively to thinning (Erdmann and Oberg 1973, Leak and Yamasaki 2012, Pothier 1996). A similar study from Bedard et al. (2018) recorded a 5-year post-thinning net growth ranging between 0.63 and 0.71 $\text{m}^2\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$ with various thinning intensities, although the net growth increment in the control was almost identical to that found in the present study (0.39 $\text{m}^2\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$). However, stands studied as part of the present work differs in age, site, geographic location, and species composition. The site studied by Bedard et al. (2018) had a notable proportion of BA in yellow birch (21.7 to 31.7 percent), but was dominated by sugar maple. In our study, the growth gain of survivors in thinned units was lower than in Bedard et al. (2018), and the decrease in mortality following treatments was also lower. This difference in survivor growth may be due to the presence of aspen trees in a dominant canopy position in our experimental units before treatment. These trees, whose d.b.h. increases rapidly at this age, were harvested first during the thinning. Marquis and Ernst (1991) had already observed that the removal of dominant trees could lead to a reduction in net increment in the stand. The net growth measured in the control plots remains higher than what was observed by Pothier (1996) over a 20-year period in a sugar maple stand in the same area where the net increment in the control only reached 0.05 $\text{m}^2\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$. However, the stands were 50 years old, and both the BA and mean d.b.h. were greater.

Influence of Thinning Intensity on the Tree-level Growth

The effect of thinning intensity on the average d.b.h. increase was not significant for trees in the larger d.b.h. class. Nevertheless, these results confirm that yellow birch can respond to thinning if the opening is sufficient. Erdmann and Peterson (1972) had already observed the responsiveness of yellow birch to thinning in northern Michigan, in the 3 years following treatment. Their study site was located in a 40-year-old even-aged stand dominated by yellow birch. Density, BA, and average d.b.h. before treatment were comparable to that of our study. The greatest increase in d.b.h. was observed after the highest intensity harvest, which involved the removal of all competitors whose crowns were within a 4.5-m radius of the selected tree. The growth gain was proportional to the intensity of the removal, as we also observed, although in our case the differences between the three intensities were not significant. In contrast, the maximum d.b.h. increment measured by Erdmann and Peterson (1972) was nearly 8 mm in a single year, which is greater than the maximum 5-year mean value of 5.7 $\text{mm}\cdot\text{yr}^{-1}$ that we observed. Although our data showed that growth gain tends to increase with increasing thinning intensity, we were unable to conclude from the results of our statistical analysis. A potential explanation is that the clearing method was the same for all treatments, which was to harvest the two largest competitors of the marked tree. Thus, the increase in thinning intensity was rather an increase in the number of trees cleared than an increased clearance of some trees. This aspect will need to be further analyzed following the planned 10-year post-treatment measurement. It would have been interesting to test the effect of several clearance intensities around the future trees. However, the constraint of operational harvesting and mechanized felling prevented us from doing so. Indeed, it was difficult to harvest trees on the opposite side of the marked trees without risking damage to its neighbors.

Influence of Diameter and Social Status on Tree-level Growth

Our conclusions regarding the effect of d.b.h. class and social status on diameter increment are similar to that of Erdmann and Peterson (1972), who stated that the response to thinning is greater in intermediate trees than in codominant and dominant trees. Indeed, growth gains measured in thinned stands compared to the control stands were substantially lower for trees with d.b.h. of 18 cm and above and for marked trees than for trees in the lower d.b.h. classes. For the larger

trees, the growth difference between treated and control stands were not statistically significant. This discrepancy could be explained either by the nature of the competition experienced or by the responsiveness of the cleared trees. First, it is possible that the larger trees, generally in a dominant or codominant position, still had sufficient access to light prior to treatment and experienced only a limited competition for sunlight and resources. Removal of neighboring trees would therefore have had only a limited effect. This hypothesis was proposed to explain the limited growth response of the larger trees after thinning in a Douglas-fir stand (Dodson et al. 2012). Secondly, it is possible that at 41 years of age, the ability of dominant and codominant yellow birches to respond promptly to thinning was not as strong as expected. Indeed, while strong responses to thinning were observed at 16, 35, and 40 years (Erdmann and Peterson 1972, Erdmann et al. 1975a, Ouimet et al. 2018), the response was rather minimal at 65 years (Erdmann et al. 1975b). Thus, yellow birch may lose its ability to respond promptly to thinning between 40 and 65 years of age.

Our results confirmed that, despite a lower response of larger diameter trees to thinning, they still contributed the most to the growth at the stand level. Other authors have made similar observations (Bedard et al. 2018, Erdmann and Peterson 1972). Although the absolute growth of dominant trees is greater than that of lower-story trees, the relative growth gain generally follows a trend of opposite direction (Marquis 1969, Miller 2000, Ward 1995). The significant effect seen for smaller diameter trees would therefore be attributable to a decline in competition, resulting in greater access to light for the remaining trees. This effect is particularly visible in trees located near logging trails. Indeed, their growth was significantly higher ($p \leq 0.01$, results not presented) than that of trees located more than 5 m from the trails. Consistent with the findings of Bedard et al. (2018), the significant difference observed between the growth of trees located within 5 m of the center of a trail and those located further away would be entirely attributable to this clearance. Finally, the observed gain in d.b.h. increment of residual trees in the treated units could be due to the retention of the most vigorous trees, whose increment is higher, during thinning. This hypothesis is supported by the fact that the increment of marked trees was significantly higher than that of nonmarked trees, even in control. Therefore, in the present study, thinning following tree marking effectively allowed to retain trees with a superior growth potential.

Since this study only includes data collected 5 years after thinning, the most pronounced benefits might not be seen until the next few years. Clearing could allow marked trees to develop their crowns, especially in density. Indeed, Erdmann and Peterson (1972) observed an increase in crown density in a large proportion of cleared yellow birch trees in the 3-year period following commercial thinning, resulting a d.b.h. increase. Although changes in crown density were not documented in this study, the increased photosynthetic capacity of these trees may also allow them to maintain their growth for a longer period than in the absence of treatment.

Implications for Management Practices

In the present study, results from the 5-year monitoring showed that commercial thinning mainly improved stand composition, increasing the proportion of yellow birch and crop trees consecutively to the priority harvesting of aspens and other unwanted species. In the studied yellow birch stand, crop trees appeared to suffer little from competition from shade intolerant species before treatment. In addition, the use of heavy machinery made it difficult to completely clear the crowns of marked trees. Thus, thinning resulted in only small gains in growth compared to a no-intervention control. In fact, the growth of the controls was still very good, especially for larger diameter and crop trees. The thinning could have been delayed for a few years without compromising stand quality and vigor. This would have increased the profitability of operations by obtaining a larger average harvest diameter. However, the probability of obtaining a lower growth response seems to increase with stand age.

In an intensive silviculture scenario, commercial thinning is normally carried out after precommercial thinning. Based on the short-term results from the present study and the scientific literature consulted, it seems that the growth response to commercial thinning of dominant yellow birch in young stands with an even-aged structure is of lesser magnitude than their response to precommercial thinning. Nonetheless, the results obtained still demonstrate the benefits of practicing of commercial thinning in a 40-year-old yellow birch stand. The primary focus of the intervention should be to improve stand composition as well as the relative importance of crop trees in the stand. The benefits for stand growth of a commercial thinning conducted later in the scenario appears to be more variable, and to be highly dependent on stand composition and age. Longer-term results from this experimental site will allow verifying how the benefits of commercial thinning change over time.

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Nonparametric Individual-Tree Growth Models for the Northern Forest

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Abstract.—Tree growth modeling is important for forest managers, but is difficult in structurally and compositionally diverse forests where growth depends on complex ecological relationships. Many of those relationships are not well studied, and traditional parametric models struggle to adequately account for them. We describe a nonparametric machine learning approach to modeling, which uses data to determine the methodology, accommodates high dimensional data, and could be well suited to capturing complicated, poorly understood interactions between predictors. We compare this approach to the traditional parametric approach by constructing diameter increment models for the United States northern forest region. In this case, the approach led us to build a gradient boosting machine that decreased the root-mean-squared error by 6.5 percent over the traditional, nonlinear least squares model, and which was especially accurate in predicting the growth of trees in less common situations, such as especially large trees and trees in forests with below- and above-average basal areas. Analysis of the model structure showed that its predictions are driven by multiple complex interactions. We explore several of them and discuss the potential of the nonparametric machine learning approach for predictive tree growth modeling and for studying ecological processes underlying tree growth.

INTRODUCTION

Forest managers depend on tree growth models to evaluate management approaches and establish forest valuations, but modeling has proven difficult in mixed-species and multi-aged forests where growth is driven by particularly complex ecological relationships. For example, recent research has demonstrated that the species identity of neighboring trees can influence growth, and that the effects of species mixing depend on the species involved (Canham et al. 2004, Fien et al. 2019, Pretzsch 2017). In many cases, trees in mixed-species stands have higher potential growth rates than those in mono-specific stands because of positive interactions between species (Pretzsch and Zenner 2017). Yet very few growth models account for species mixing, preventing managers from accounting for mixing effects in forest valuations and inhibiting efforts to take advantage of mixing effects through silvicultural interventions. Stand structural diversity is similarly absent from most operational growth models but has been shown to relate to tree growth in complicated ways (Ali 2019). Measures of structural diversity are positively correlated to growth in some settings (e.g., Dănescu et al. 2016, Lei et al. 2009) and negatively correlated in others (e.g., Edgar and Burk 2001, Liang et al. 2005), depending on the particular species and their development. These are complicated relationships that have not been studied in most forest types (O'Hara 2014, Pretzsch et al. 2017).

One approach to modeling growth in complex forests has been to shift analytical attention from stand to neighborhood dynamics (Canham and Uriarte 2006). This approach conceptualizes a forest stand as a collection of distinct patches of land (neighborhoods) that are typically 0.01 to 0.1 hectares in size and are assumed to be developing independently from one another (Bugmann

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2001). Emphasis on neighborhood dynamics grew out of ecological research demonstrating that plant-to-plant interactions are primarily local, neighbors' effects attenuate with distance, and beyond a certain distance, plants have no detectable effect on one another (Stoll and Weiner 2000). To simplify analyses and data collection, neighborhood-scale models can ignore the specific locations of trees within each neighborhood, thereby offering a compromise between high resolution, difficult to apply distance-dependent models, and low resolution, easy to apply stand-scale models (Bugmann 2001). Historically, neighborhood-scale models have been used to model long-term system-level dynamics (e.g., Forsyth et al. 2015), often under the moniker "gap models," and the majority of research attention has been directed toward representing regeneration, recruitment, and mortality based on an understanding of ecological processes (Weiskittel et al. 2011). These "mechanistic" models rely on causal relationships and ecological theories and are well suited to studying ecosystem changes (Cuddington et al. 2013), but they are often less accurate than empirical models in predicting overstory tree growth, more difficult to initialize, and incapable of capturing ecological processes that have not been well studied (Taylor et al. 2009), limiting their application for practitioners.

There are also many statistical forest growth models built for operational decision-making (Weiskittel et al. 2011). These are generally parametric models constructed with traditional regression-based techniques, which predict the growth of individual trees and employ stand-scale competition metrics (Weiskittel et al. 2011). These models could be adapted to a neighborhood framework by incorporating neighborhood-scale competition metrics in place of stand-scale metrics, potentially improving overstory growth predictions and making neighborhood-scale models easier to initialize. Still, existing parametric models fail to account for many complex and poorly understood effects, which could limit their accuracy usefulness in mixed-species, multi-aged forests.

In this paper, we explore the potential for integrating nonparametric models into the neighborhood-scale model framework, using a machine learning approach. Nonparametric models are especially good at uncovering complex and poorly understood relationships in data (Breiman 2001). They use data to determine their own structures and make minimal assumptions about the processes that generated the data. This is in contrast to the traditional parametric approach, in which the data are assumed to have come from a stochastic model and previous research guides the selection of a model form and the predictors to be used (Breiman 2001). Nonparametric models are trained using machine learning, which is a branch of artificial intelligence that uses algorithms to allow computers to "learn" from data. Breiman (2001) points out three advantages of machine learning over traditional modeling, which he refers to as the three important "lessons" of machine learning: *First*, machine learning recognizes that many different models can do a good job explaining the same phenomenon and takes an experimental approach to model selection; *second*, machine learning does not shy away from complex model formulations when they can improve predictions; and *third*, machine learning accommodates high dimensional data, seeking relationships among many interrelated variables. For these reasons, it has been successful in modeling complex processes with interrelated predictors and in situations where extensive or high-dimensional data are available.

Nonparametric models do have drawbacks, though. Because they are entirely data-driven, they do not ensure biologically robust behavior, which could be problematic when using models for long-term simulations. They also cannot extrapolate well beyond the limits of their training data and tend to be more computationally demanding and more difficult to interpret.

Still, it appears that nonparametric techniques could be helpful for modeling tree growth in mixed-species, multi-aged forests, since large amounts of forest inventory data have been

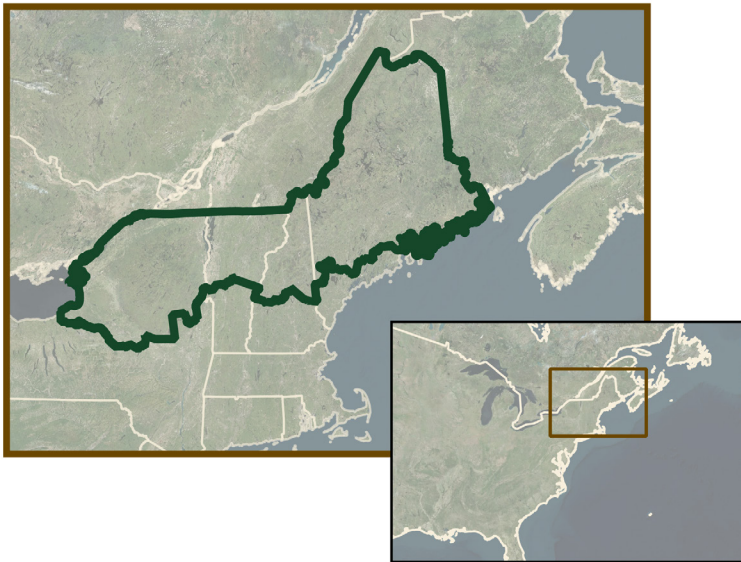


Figure 1.—Northern forest region.

collected in many places over extended time periods (Kershaw et al. 2017), which could provide sufficient information for nonparametric models and alleviate problems with extrapolation. Forest ecologists have begun using nonparametric models regularly for predicting nonlinear ecosystem behaviors (Liu et al. 2018), but their application to forest growth modeling has mostly been limited to tree mortality (e.g., Fan et al. 2006, Guan and Gertner 1991, King et al. 2000), which has been especially hard to predict using traditional parametric techniques.

We illustrate the nonparametric approach by constructing a neighborhood-scale, tree diameter increment model, using extensive inventory data from the ecologically complex United States northern forest region. We compare the nonparametric model to a second, parametric model that we parameterized to the same dataset to get a sense of its efficacy, and we explore a few of the unexpected relationships that it uses to guide its predictions. Finally, we discuss the potential for nonparametric techniques in predicting and studying tree growth in complex forests.

STUDY AREA

The “northern forest” covers 36 counties in the New York Adirondacks and northern Vermont, New Hampshire, and Maine (Fig. 1). It is located between the temperate forests of the eastern United States and the boreal forests of Canada, and contains characteristics of both biomes, giving it a diverse mixture of tree species and site conditions. Trees in the training data (described in the next section) belong to 28 different species groups and are located in 17 different forest types and 14 different landscape positions. The most common species groups (by number of stems) are fir (*Abies balsamea* (L.) Mill.), spruce (mostly *Picea rubens* Sarg. and *Picea mariana* (Mill.) Britton, Sterns & Poggenburg), soft maple (*Acer rubrum* L.), hard maple (*Acer saccharum* Marshall), cedar (*Thuja occidentalis* L.), beech (*Fagus grandifolia* Ehrh.), yellow birch (*Betula alleghaniensis* Britt.), paper birch (*Betula papyrifera* Marshall), hemlock (*Tsuga canadensis* (L.) Carrière), and eastern white pine (*Pinus strobus* L.). Elevations in the region range from 0 to 1,917 meters above sea level.

The region is well suited to studying the complexities of tree growth because its forests tend to be complex. Most are naturally regenerated, second-growth forests with varied management histories. In the training data, some 68 percent of plots contain three or more species growing together, while the spread of within-plot tree diameters averages 35 cm.

DATA

Data were obtained from the USDA Forest Service's Forest Inventory and Analysis (FIA) program (<https://apps.fs.usda.gov/fia/datamart/datamart.html>, downloaded December 6, 2020) from remeasured plots in the northern forest region. We used data from the current national standard plot design, which was adopted in the mid-1990s (Woudenberg et al. 2010). These plots are systematically located and evenly distributed across the region. Each plot is made up of four 168-m² subplots with a 13.5-m² microplot inside each subplot. Trees greater than 12.7 cm diameter at breast height (d.b.h.) are measured on subplots, and trees between 2.54 and 12.7 cm d.b.h. are measured on microplots.

FIA data relate to numerous tree-, plot-, and stand-level attributes, and are collected through ground sampling and remote sensing. Our objective was to build a model for operational decision-making, so we focused on attributes that can be measured reasonably easily by practitioners. They include d.b.h., species, compacted crown ratio (CR), crown class, tree class (a measure of general quality), forest type, stocking level, landscape (physiographic) position, site class, slope, aspect, elevation, latitude, and longitude. We also used existing data to calculate a number of new attributes, including subplot basal area (BA), tree overtopping basal area (BAL), and species-specific subplot BA and tree BAL. To keep the data and resulting model relevant to practitioners, we grouped tree species into species groups and FIA forest types into more general forest types. Our groupings were designed to match common inventory protocols that we have observed. Finally, we removed trees from the analysis that died during the remeasurement period and removed all plots with missing data. The final dataset includes 399,358 observations from 11,286 different plots. Remeasurement intervals on the plots ranged from 2.9 to 7.8 years and averaged 5.1 years.

Twenty percent of the plots were randomly selected, and their data were set aside for testing final models, to account for over-fitting and allow a fair comparison between different modeling approaches. This splitting was based on plots rather than individual trees to make sure that the testing data are truly independent. The data from the remaining 80 percent of plots were used for exploratory analysis, to compare different modeling methodologies, and to train the final models.

All of the data acquisition and processing, and the analysis that follows, was done using the programming software R, version 4.0.1 (R Core Team 2020). Much of the general data manipulation and visualization was carried out with R Tidyverse packages (Wickham et al. 2019); models were trained, tuned, and compared using Kuhn et al.'s (2020) "caret" framework. Detailed methods are available at <https://github.com/nealmaker/tree-growth-nf>.

METHODS

Model Development

We used all 18 aforementioned predictors to train our nonparametric diameter growth model. Remeasurement intervals varied in the data, and we annualized diameter growth rates to make them comparable. To our knowledge, no model-agnostic, nonlinear interpolation methods exist for annualizing remeasurement data, so we assumed linear growth through the remeasurement period and trained models on average annual d.b.h. growth rates.

We used a number of pre-processing steps on predictors so they could be widely used across methods and to increase model accuracy (Kuhn and Johnson 2013). Nominal categorical predictors were dummy-encoded; numeric predictors were centered, scaled, and normalized using Yeo-Johnson transformations (Yeo and Johnson 2000); and highly correlated predictors were filtered.

While parametric models prevent over-fitting by using simplified, predetermined model forms that cannot be bent out of shape to fit the noise in the training data, nonparametric models are more flexible, and over-fitting must be deliberately addressed (Hastie et al. 2017). We did this with 10-fold cross validation and model tuning, using the *recipes* framework developed by Kuhn and Wickham (2020). Pre-processing steps were applied independently to each training in the cross validation, to prevent information from the reserved fold from biasing the estimated prediction error.

We spot-checked 18 different algorithms representing a wide variety of modeling methods to find the most promising ones. We were most concerned with accuracy, which we measured using root-mean-squared error (RMSE), but we also compared prediction speed and model object size (megabytes) to account for how easily models could be incorporated into growth simulators. We used a random subset of the training data and parallel processing to speed the process. Nonlinear methods like model trees, random forests, gradient boosting machines, and support vector machines were the most accurate in this particular case, while regularized models were less accurate, but smaller and faster at making predictions. We chose a gradient boosting machine as the best compromise, because it offered high accuracy with relatively fast prediction speeds and was reasonably small compared to many of the other nonlinear methods.

Having chosen the best algorithm for the application, we reparameterized the model using all of the training data and a more organized tuning process described by Boehmke and Greenwell (2020, section 12.3.3). The final tuned model has a shrinkage rate of 0.5 and uses 14,000 regression trees, with each tree having a minimum terminal node size of 15 observations and a maximum tree depth of two branches. See Hastie et al. (2017, pp. 337–388) for a more detailed description of gradient boosting trees and their tuning parameters.

A Parametric Model for Comparison

As a point of comparison, we also built a nonlinear least squares model of individual tree diameter increment, based on a similar model that Weiskittel et al. (2016) built for the New York Adirondacks. We experimented with nonlinear mixed-effects modeling, treating plots as random, but found no improvement over nonlinear least squares modeling. Both approaches have been used successfully to model individual tree growth in the Northeast (Kuehne et al. 2020). Our model used the form:

$$ADI = \exp(b_1 + b_2 \cdot \ln(DBH) + b_3 \cdot DBH + b_4 \cdot BAL + b_5 \cdot \sqrt{BA} + b_6 \cdot SC)$$

where *ADI* is the annual diameter increment (cm·yr⁻¹), *DBH* is diameter at breast height (cm), *BAL* is overtopping basal area (m²·ha⁻¹), *BA* is plot basal area (m²·ha⁻¹), and *SC* is site class. These predictors have been well studied in the northeastern United States in relation to diameter increment (Teck and Hilt 1991, Westfall 2006), their use in predicting diameter increment has a strong conceptual basis (Weiskittel 2011), and they were found to be important predictors for the FIA data. The equation was fit to the training data for each species group to obtain species-specific coefficients.

We used McDill and Amateis' (1993) nonlinear “two-step” interpolation method to account for the fact that different plots in the training data had different remeasurement intervals. The method assumes that the diameter growth rate over the period varies according to the model form. Nonlinear interpolation has been shown to be more accurate than assuming a linear growth rate over the remeasurement period (Cao 2010, McDill and Amateis 1993), or using the remeasurement interval as a predictor (Juma et al. 2014).

Model Assessment

We compared the nonparametric model to the parametric model based on its ability to accurately predict d.b.h. growth in the independent testing data. The models predict annualized growth increments, while growth was actually observed over multi-year remeasurement intervals. To predict whole-interval growth (Δ DBH) comparable to observed growth, we applied the models iteratively to each observation, predicting 1 year's growth at a time and updating the DBH, BA and BAL before predicting the next year's growth. We assumed a linear change in BA and BAL over each remeasurement period (after Weiskittel et al. 2016). Overall accuracy was assessed using RMSE and mean absolute error (MAE).

We also used several model-agnostic interpretation tools to explore the structure of the nonparametric model. Nonparametric models like the gradient boosting machine can be very complicated, and instead of trying to fully describe the model's structure, we chose a couple of examples of important growth effects to illustrate the interpretive process. To start, we calculated permutation feature importance (Fisher et al. 2019) to see which predictors contribute the most to the models' predictions. Then we used Friedman's H-statistic to search for potential interactive effects (Friedman and Popescu 2008) and visualized several of them with partial dependence plots (Friedman 2001). We implemented all three techniques using Molnar et al.'s (2018) *iml* package for R.

RESULTS

The mean observed Δ DBH over all species and tree sizes was 1.27 cm, for remeasurement intervals that averaged 5.1 years. The distribution of observed Δ DBH was skewed right, with 90 percent of observations falling between 0 and 3 cm. Our nonparametric gradient boosting machine was more accurate in predicting Δ DBH than the parametric nonlinear least squares model, reducing the RMSE by 6.5 percent and the MAE by 7.9 percent (Table 1). These predictive gains came at the cost of speed and size, with the nonparametric model taking 27 times as long to make predictions and using almost 44,000 times the space in memory.

Both models are relatively unbiased overall, but the nonparametric model is less biased than the parametric model in predicting the growth of especially slow- and fast-growing trees (Fig. 2) and in predicting growth in trees with less common attributes, such as large d.b.h. (Fig. 3a) and small or large CR (Fig. 3b), and in less common settings, such as below- or above-average BA (Fig. 3c) and BAL (Fig. 3d).

Table 1. —Performance metrics for the parametric nonlinear least squares model (NLS) and the nonparametric gradient boosting machine (GBM). Mean error is the mean of observed responses minus the mean of predictions. Speed is the time to make 1,000 predictions on our computer and is relative.

Metric	NLS	GBM
RMSE (cm)	0.364	0.341
MAE (cm)	0.269	0.248
Mean Error (cm)	0.005	0.003
Speed (sec)	0.07	1.97
Size (MB)	0.003	131

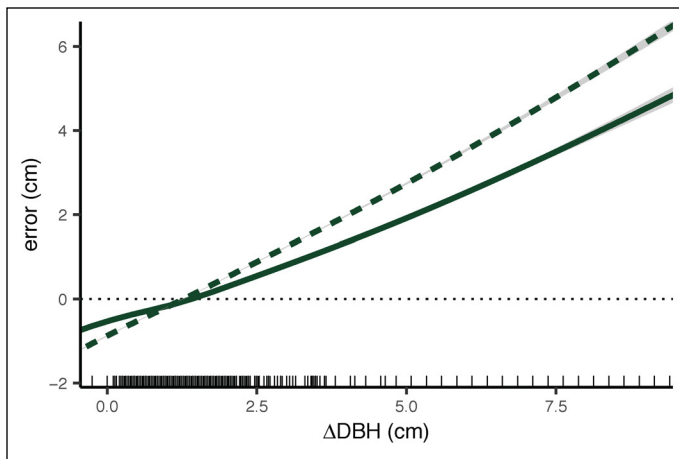


Figure 2.—Prediction error trends (observed minus predicted) based on observed Δ DBH, for the gradient boosting machine (solid line) and nonlinear least squares model (dashed line). Trends are drawn with generalized additive models and shaded regions show 95 percent confidence intervals. The rug plot on the x axis shows the Δ DBH distribution, with a higher rug density indicating a greater number of observations.

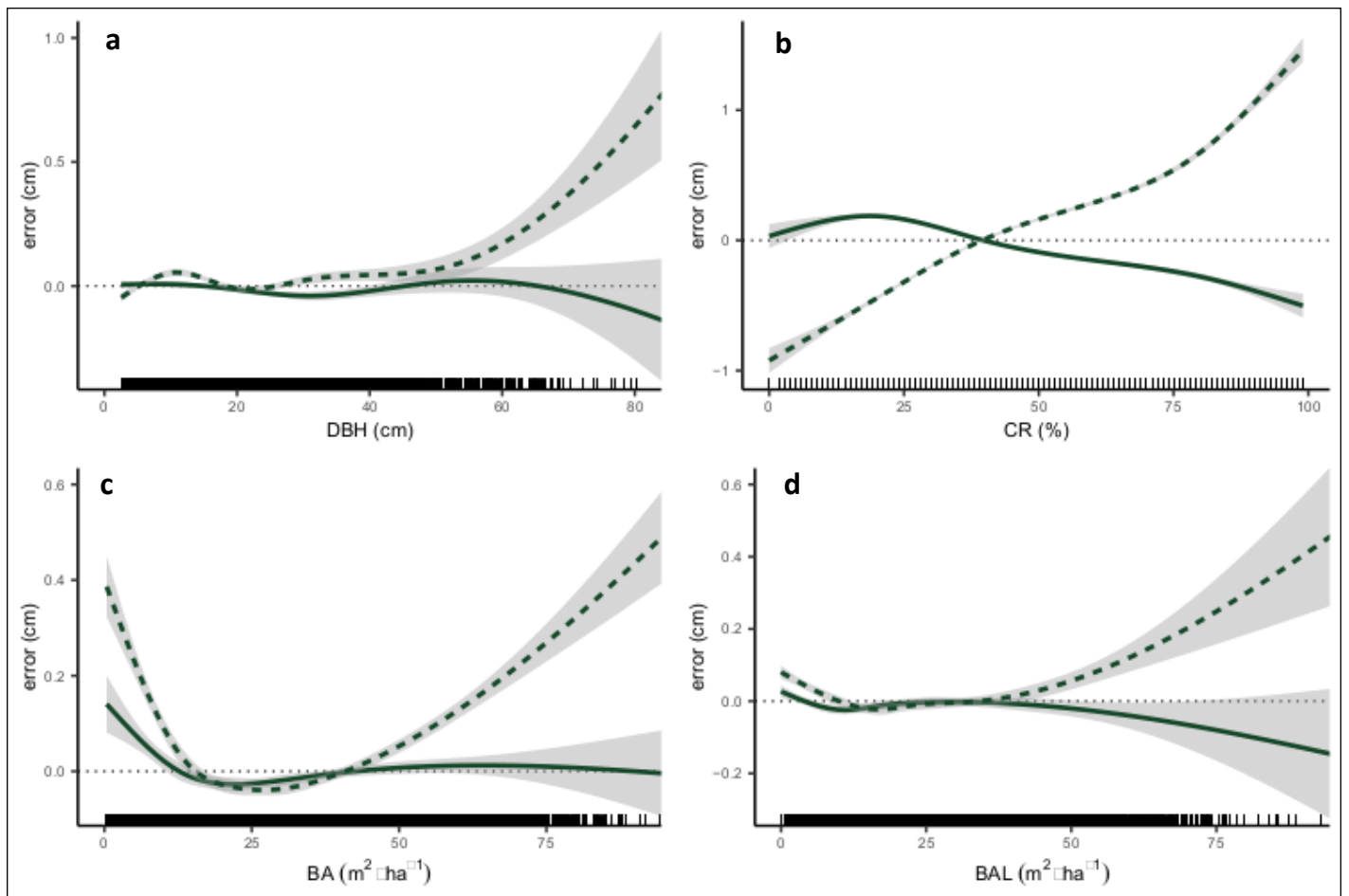


Figure 3.—Prediction error trends (observed minus predicted) based on (a) DBH, (b) CR, (c) BA, and (d) BAL, for the gradient boosting machine (solid line) and nonlinear least squares model (dashed line). Trends are drawn with generalized additive models and shaded regions show 95 percent confidence intervals. Rug plots on the x axes show predictors' distributions, with higher rug densities indicating more observations.

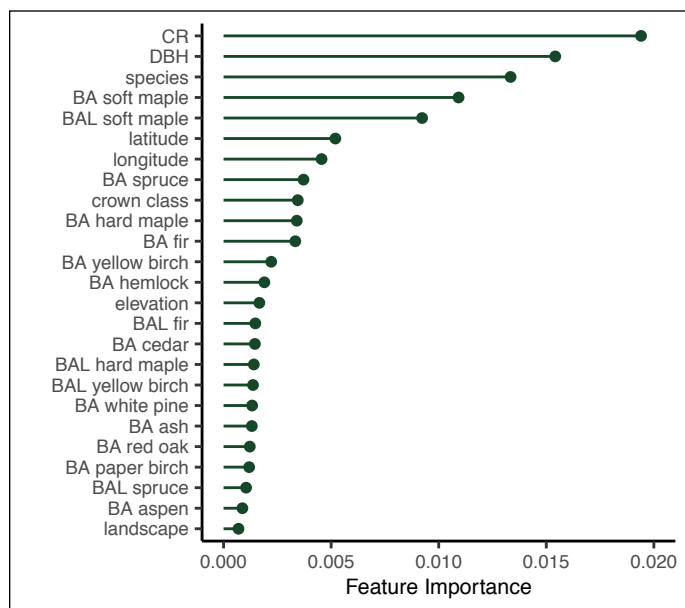


Figure 4.—Permutation feature importance of the 25 most important predictors. BA and BAL are decomposed by species.

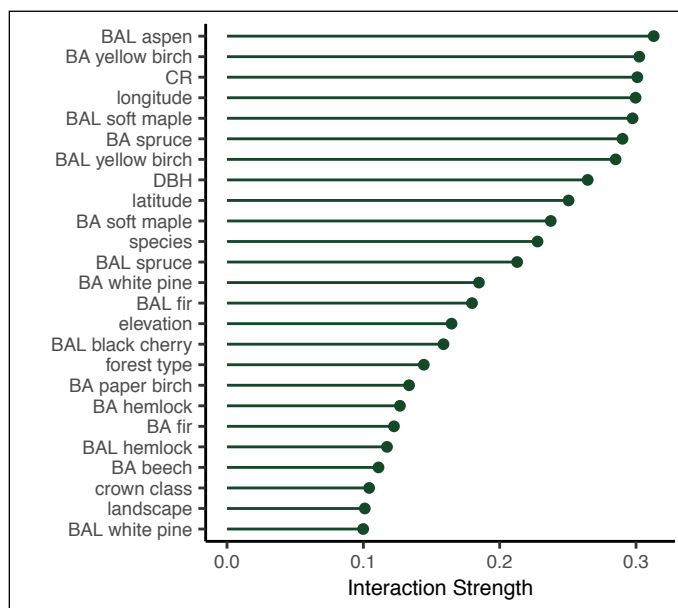


Figure 5.—Interaction strengths of the 25 predictors demonstrating the most interaction, calculated using Friedman's H-statistic. BA and BAL are decomposed by species.

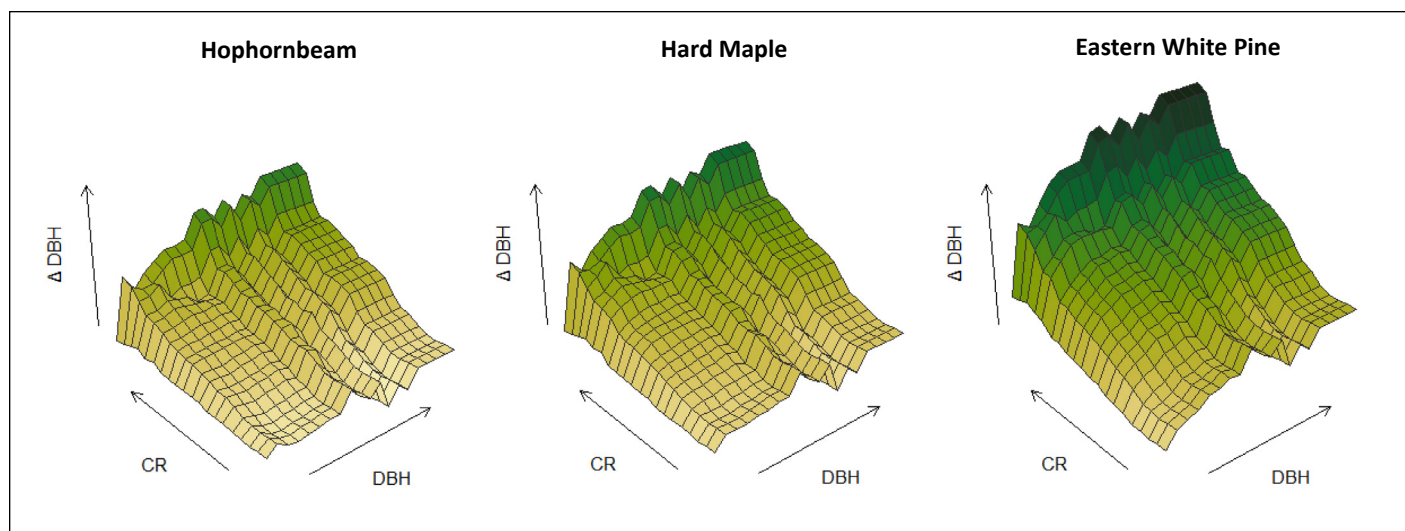


Figure 6.—Relationship between DBH, CR, and predicted Δ DBH for three individual species groups, using partial dependence plotting. The shape of the response curve for each predictor changes depending on the other predictors, indicating that the predictors interact with one another.

Subplot BA was the most important predictor in the nonparametric model (with a feature importance score of 0.035), followed by CR (0.019), BAL (0.019), DBH (0.015), and species (0.013). Figure 4 shows the relative importance of the 25 most important predictors with species-specific BAs and BALs listed separately.

The predictors with the highest overall interaction strengths in the nonparametric model are shown in Figure 5. Calculations of specific interaction strengths between predictors with high overall strengths revealed several important interactions that influenced the model. The most important is a three-way interaction between species, d.b.h., and CR. Figure 6 illustrates the interaction using three of the 28 species groups. Generally, the effect of CR is amplified at larger d.b.h., the effect of d.b.h. is amplified at larger CR, and both the CR and d.b.h. effects are larger in some species (e.g., eastern white pine) than in others (e.g., hophornbeam). A second interaction

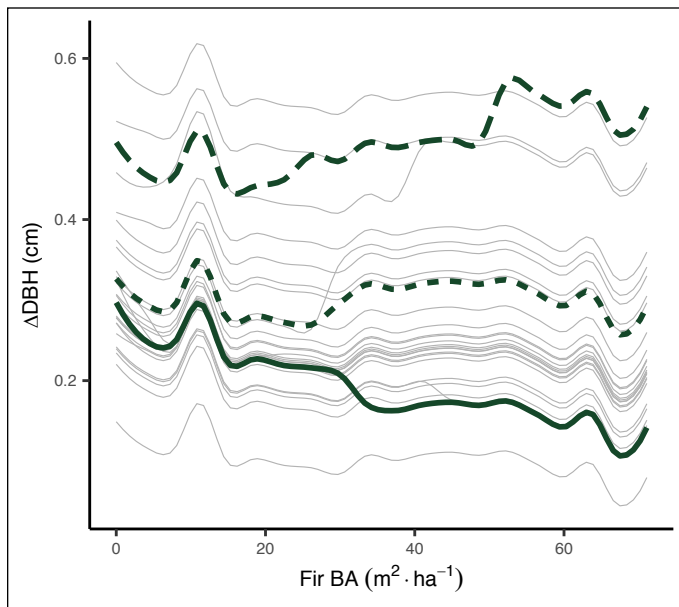


Figure 7.—Relationship between fir BA and predicted Δ DBH for individual species, using partial dependence plotting. Three species have been highlighted: aspen (dashed line on top) demonstrates increased growth at higher fir BA, hemlock (dotted line in middle) demonstrates growth poorly correlated to fir BA, and yellow birch (solid line on bottom) demonstrates reduced growth at higher fir BA.

occurs between fir BA and species (Fig. 7). For most species, the model predicts reduced d.b.h. growth on plots with higher fir BA, but fir BA does not affect predicted growth for other species like hemlock. Aspen actually experiences increased predicted growth rates at higher fir BA. These are two of the more important interactions driving the nonparametric model, but they are not the only ones. Interaction strengths suggest additional interactions related to latitude and longitude, and to a number of different species-specific BAs and BALs.

DISCUSSION

We did not observe large gains from the nonparametric model overall or for average trees in common situations, but the nonparametric model is more accurate for trees in abnormal situations, such as for larger diameter trees, trees with above- or below-average crown sizes, and trees growing with above- or below-average competition. Part of that advantage likely comes from the nonparametric model's use of numerous predictors. While parametric techniques focus on the most important predictors to build a robust and parsimonious model, the nonparametric approach also makes use of less important predictors whose simple effects might add to the predictive ability when they are aggregated.

The nonparametric model also accounts for some complex interactions that the parametric model does not capture. We illustrated the three-way interaction we found between species, d.b.h., and CR, and the uneven effect of fir BA on different species as examples. Interaction strengths pointed to several more potential interactions, and there could be many more among less important predictors, which would contribute little to overall accuracy, but could be important in specific situations. Parametric techniques could be used to model interactions like these, but only if they were understood ahead of time and deliberately included.

All three of Breiman's (2001) "lessons" probably came into play in uncovering these interactions: *First*, the nonparametric approach did not limit model selection to match a preconceived conception of growth dynamics, and was able to find a particularly good model algorithm that had not been tried in this context before; *second*, the nonparametric approach did not impose limitations on model complexity, and employed a complicated model more capable of representing interactions; and *third*, the nonparametric approach embraced the high dimensional data, which

contained information about interactions that might have been missed otherwise. It is important to note that these benefits depend on nonparametric models following the data more or less blindly. Cross validation and other resampling methods can prevent over-fitting, but any biases in the data will lead to inaccurate models. This is true of parametric models as well but is probably more acute for nonparametric models.

When extensive, unbiased data are available, the complex, flexible models that machine learning can produce may be especially good at uncovering the subtleties of neighborhood-scale growth dynamics without requiring expensive inventory or parameterization. In this way they could be a boon to practitioners working in diverse and complex forests. But several questions remain about their effectiveness for predictive modeling. First, can nonparametric models accurately predict forest growth over longer time periods? Parametric models are somewhat more mechanistic in that their structures are often informed by biological relationships, which could give them an edge in longer-term simulations. Suitable long-term reinventory data are needed to determine if nonparametric models' more empirical forms disadvantage them. And second, are nonparametric models' relatively subtle gains in predictive ability worth their cost in increased computing power and complexity? Small gains in describing growth variability could be quite valuable to managers of diverse hardwood forests, where some trees are worth much more than others and the nuances of growth are more important. However, this information will probably be less valuable to managers of simpler forests geared toward fiber production.

Regardless of their usefulness for predictive modeling, it does seem clear that nonparametric techniques are very valuable for studying tree growth in complex forests. Existing forest inventory data contain a wealth of information for machine learning techniques to mine, and the rapidly expanding new field of interpretable machine learning is devoted to studying machine learning models to understand the relationships they glean from data (Molnar 2020). Variable importance, interaction scores, and partial dependence plots are a few of the better-established techniques, but there are many more, and they are growing more sophisticated as the field matures. Models that used to be considered black boxes are now becoming powerful microscopes, capable of finding complicated relationships between multiple variables.

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Comparison of Structural and Compositional Attributes of Northern Hardwood Forests in Michigan and Minnesota

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Abstract.—Northern hardwood forests are structurally and compositionally diverse resulting in multiple “types” of northern hardwood forest communities. Within the northern Great Lakes Region of the United States (Michigan, Minnesota, and Wisconsin), Minnesota represents a transition zone for multiple tree species with some tree species reaching their western, northern, or southern edge of their range including sugar maple (*Acer saccharum*). To explore the potential influence of range limits on the structure and composition of northern hardwood forest communities, I utilized the Forest Inventory and Analysis database on a subset of counties in eastern Minnesota and the western Upper Peninsula of Michigan. One hundred and eleven plots across 10 counties in the two states were coded as the maple/basswood/beech forest type. Between the two states, there were many similarities in site conditions and overall metrics of forest communities (average diameter, age, regeneration density). However, Minnesota and Michigan northern hardwood forests are compositionally different; Michigan northern hardwood forests were more commonly dominated by sugar maple and red maple (*Acer rubrum*), while American basswood (*Tilia americana*) and northern red oak (*Quercus rubra*) were more common in Minnesota. A nonmetric multidimensional scaling ordination showed clear separation between plots from Michigan and Minnesota in ordination space. As interactions among climate change, invasive species, ownership patterns, and disturbance regimes continue to influence species composition in forest communities, understanding the range of potential northern hardwood community composition and structure can provide opportunities to explore alternative silvicultural approaches.

INTRODUCTION

The northern hardwood forest cover type encompasses an extensive area of the northern Great Lakes Region (defined as Michigan, Minnesota, Wisconsin, USA, and Ontario, Canada; hereafter referred to as GRL), extending across the northeastern United States and southern Canadian providences (Braun 1950). This cover type represents a diverse mix of overstory species, soil conditions, moisture regimes, and disturbance dynamics. “The Manager’s Handbook for Northern Hardwoods in the North Central States” (Tubbs 1977) documents seven different forest types; only two of the forest types are dominated by sugar maple (*Acer saccharum* Marshall). The other five forest types have lesser amounts of sugar maple and a broader mix of hardwood and conifer species including northern red oak (*Quercus rubra* L.), paper birch (*Betula papyrifera* Marshall), and eastern hemlock (*Tsuga canadensis* (L.) Carrière). However, sugar maple dominated forest types are often the “poster child” for northern hardwood management (Crow et al. 2002, Hupperts et al. 2018, Neuendorff et al. 2007, Scheller and Mladenoff 2002).

The prevalence of research on sugar maple dominated forest types is likely due to in part to its historic and current economic value (Dey et al. 2017, Godman and Mendel 1978). After the

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extensive cut-over of eastern white pine (*Pinus strobus* L.) and other conifer species in the GLR during Euro-American colonization, lumber companies that did not move westward had to switch to harvesting hardwood forests (Whitney 1987). There was a push to move from exploitive high-grading to exploring concepts of sustained yield. One research forest to explore this concept was the Dukes Experimental Forest (EF), located outside of Marquette, MI, which was established in 1926 (Kern et al. 2014). The Dukes EF had limited selective harvesting of American elm (*Ulmus americana* L.) and American basswood (*Tilia americana* L.) and was a mostly unharvested with northern hardwood forest dominated by sugar maple (>80 percent of merchantable sized trees) where researchers explored both even- and uneven-aged management. However, one of the most well known products from the Dukes EF was the Arbogast marking guide; it was cited as being applied to millions of hectares in the Lake States (Arbogast 1957). The Arbogast marking guide focuses on the development of a well regulated and balanced diameter distribution through the use of ratios, commonly called the q factor, which creates a reverse-J diameter distribution and is implemented with a relatively frequent cutting cycle (10 to 15 years) using single-tree selection system. This silvicultural system has been documented through multiple long-term experiments in the GLR, e.g., Dukes EF, Argonne Experimental Forest, and Ford Forestry Center (Bassil et al. 2019, Campione et al. 2012, Kenefic and Kern 2015, Metzger and Tubbs 1971, Neuendorff et al. 2007) to maintain high quality sugar maple dominant forests (see Webster et al. 2018 for noted shortcomings).

However, not all northern hardwood forests are dominated by sugar maple. Sugar maple reaches its western range in Minnesota which roughly corresponds with the border of the Prairie Parkland province (Godman et al. 1990). The northern range of sugar maple extends slightly north of Minnesota into the Canadian province of Quebec. Minnesota is also the western and/or northern range limit(s) for other common northern hardwood associates including eastern hemlock, yellow birch (*Betula alleghaniensis* Britton), and northern red oak (Burns and Honkala 1990). Thus, the composition of northern hardwood forests in Minnesota are likely different than northern hardwood forests of northern Wisconsin and the Upper Peninsula of Michigan and thus may require different silvicultural strategies. There has been limited work to explore if structural and composition differences exist among northern hardwood forests in the GLR region (but see Burton et al. 2009).

The overarching goal of this paper is to explore and quantify structural and compositional differences within forest classified as northern hardwood in two regions, northern Minnesota and the Upper Peninsula of Michigan, using the Forest Inventory and Analysis (FIA) database. By assessing current species composition and structure within the northern hardwood forest type in the GLR, we can increase our understanding of the range of variability within this forest type and thus explore potential alternative management practices.

METHODS

Sites

The GLR of Minnesota, Wisconsin, and Michigan covers four of Bailey's (1983) ecosystem provinces: Prairie Parkland, Tall-grass Prairie, Laurentian Mixed Forest, and the Eastern Deciduous Forest. Topography and soil conditions have been influenced by past glacial activity, creating a landscape with low topographic relief and a wide variety of soil types ranging from sandy outwash plains to rich peat bogs (Stearns 1997). Nutrient availability and water holding capacity greatly influence forest composition and cover; northern hardwoods are commonly observed on mesic, nutrient rich sites in both Michigan and Minnesota (Aaseng et al. 2011, Burger and Kotar 2003).

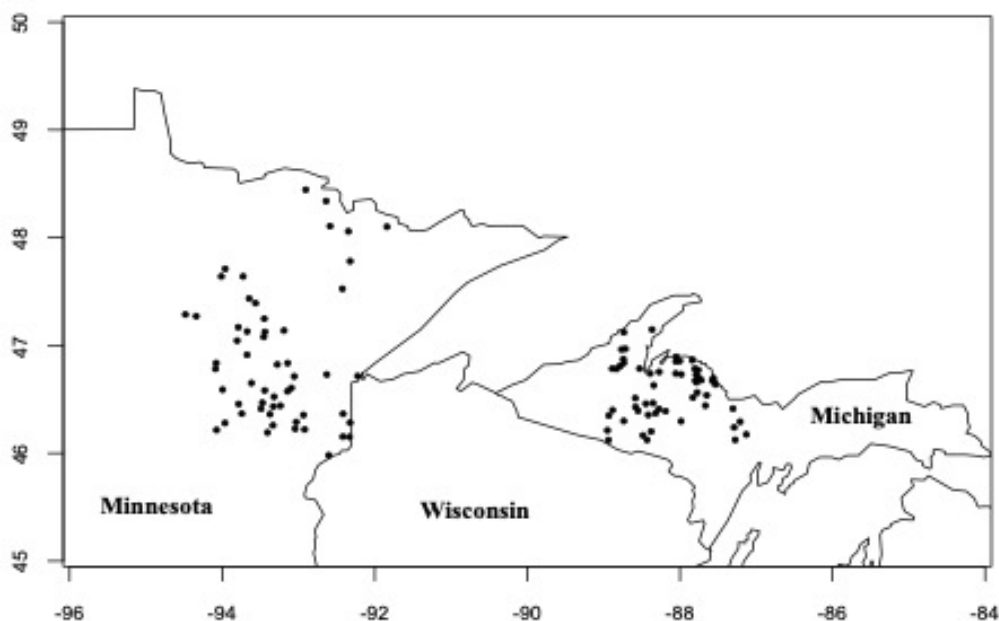


Figure 1.—Locations of FIA plots in Minnesota and Michigan used in analysis. Publically available plot data were used in mapping so plot locations represent “fuzzed” data.

Ten counties were selected for the study in Minnesota and Michigan which cover a range of environmental conditions, especially distance from a Great Lake (Fig. 1). Minnesota counties included in the sampling were: Aitkin, Carlton, Cass, Crow Wing, Itasca, Pine, and St. Louis. Michigan counties included in the sampling were: Baraga, Houghton, Iron, and Marquette. This does not represent a full list of counties in which northern hardwoods are present in Michigan and Minnesota but does represent the northern hardwood forest type for the region. More eastern counties of the Upper Peninsula of Michigan were not selected for this study due to the increased presence of American beech (*Fagus grandifolia* Ehrh.), which reaches its western range in the central Upper Peninsula of Michigan. Current impacts of beech bark disease (*Cryptococcus fagisuga*/*Neonectria* spp. complex) are influencing the forest dynamics of eastern northern hardwood forests (see Nyland et al. 2006 for the discussions). Thus, northern hardwood forests were selected in the western and central Upper Peninsula of Michigan.

Across the 10 counties included in the study, the climate is characterized by cold winters and warm, humid summers. Temperatures can range from 32 °C with high humidity (80 percent) during the growing season and –35 °C during the winter months (Neary et al. 2012). Average annual precipitation ranges from 50 to 60 cm in northern Minnesota (Neary et al. 2012); average annual precipitation in Houghton County, Michigan is 85.4 cm. The majority of precipitation falls within the growing season. However, areas close to the Great Lakes are influenced by “lake effect” with smaller seasonal differences in temperatures (i.e., warmer winters and cooler summers) and greater “lake effect” snow (Norton and Bolsenga 1993).

Current forest cover has been greatly influenced by recent management decisions during European colonization including agricultural conversion and exploitive logging practices during the early 20th century (Stearns 1997). Agricultural conversion and subsequent increases in urban communities have decreased forest cover by 40 percent in the GLR (Schulte et al. 2007). Destructive logging practices in the early 20th century shifted forest composition to more early successional broadleaf species (i.e., aspen (*Populus* spp.)) and reduced the abundance of long-lived conifers (i.e., eastern white pine). Additionally, destructive high-grading practices in northern hardwood forests were common in the region (Erickson et al. 1990). While both states include a diverse mix of federal, tribal, state, county, nonprofit, private industrial, and private

nonindustrial family forests (Windmuller-Campione et al. 2020), there are some differences within the ownership patterns. Within Michigan, 61 percent of the 8.1 million hectares of forest land is owned by private individuals and organizations; state and local and federal management contributes 23 percent and 15.5 percent, respectively (USDA Forest Service 2020a). Within private ownership in Michigan, there are 1.2 million hectares managed by private industrial forest corporations. Private landowners are still the biggest portion of land owners in Minnesota; they own 45 percent of the approximately 7.1 million hectares of forest land (USDA Forest Service 2020b). State and local organization and federal organization manage 38.7 percent and 16.5 percent of forested lands, respectively. Within private ownership in Minnesota, less than 500,000 hectares are owned and managed by private industrial forest corporations.

Data

The United States Department of Agriculture (USDA) Forest Service's Forest Inventory and Analysis (FIA) program is responsible for the collection of a national-scale forest inventory across all ownerships in the nation (Oswalt et al. 2014). Currently, data are collected using a nationally consistent three-phase sampling design (Bechtold and Patterson 2005). Phase 1 of the sampling design uses satellite imagery to stratify forested and nonforested conditions. Forests are defined as lands that have a minimum of 10 percent coverage of tree species canopies, are at least 0.4 ha in size, and are at least 36.6 m wide. Phase 2 of the FIA program utilizes Phase 1 land cover classification to establish forest plots approximately one every 2,428 ha of forested land. The Phase 2 plots consist of four, 7.2-m fixed-radius circular subplots arranged in a triangle with one subplot in the center. Within each subplot, overstory trees (diameter at breast height [d.b.h.] >12.7 cm) are assessed. Within each of the four subplots there is a series of microplots where saplings (d.b.h. 2.54 to 12.6 cm), seedlings (d.b.h. <2.54 cm), and other vegetative variables are measured. The sapling and overstory layer were combined for analysis. Phase 3 plots include additional measures for forest health, soils, and other environmental variables and are completed on a subset of Phase 2 plots. For this study, Phase 2 plots were used. Data are freely available and open to the public (<https://apps.fs.usda.gov/fia/datamart/datamart.html>).

The FIA database was queried for all single-condition plots sampled in 2014 and 2015 classified as maple/beech/birch (forest type code 800) located in six counties in Minnesota and four counties in Michigan. Forest condition classes are defined as portions of plots with distinct differences in vegetation cover or land management (Woudenberg et al. 2010). This resulted in a total of 111 plots with 56 in Michigan and 55 in Minnesota. The dataset does not represent a full inventory cycle or capture all plots classified as the northern hardwood type in either Minnesota or Michigan during the sampling years. However, due to the updated FIA grid systems, the years and counties selected represent an unbiased estimate of northern hardwood forests in of the selected regions.

Analysis

For each plot, measures of overstory and understory density were expanded to calculate trees per hectare (TPH) and basal area per hectare. Additional variables including average diameter (cm), average height (m), site index (m), overstory species richness, overstory evenness, and overstory Shannon's diversity were summarized at the plot level. Student t-tests with an unequal variance in R (R Core Team 2019) were used to test for differences in structure and composition between the two states, Michigan and Minnesota. To further explore differences in composition and structure, diameter distributions using 5-cm diameter classes and average basal area per hectare by species was constructed for each state. Species whose average composition was less than 1.5 m² ha⁻¹ of basal area were grouped into other conifers or other broadleaves. Each of these pooled categories represented on average less than 3 m² ha⁻¹.

Table 1.—Average structural attributes for the overstory and seedling layers and site characteristics with associated standard errors in parenthesis by state. Student t-test in R with unequal variances were used to test for statistical differences between the two states for each individual variable.

	Michigan		Minnesota		T-value & significance	Degrees of freedom
Overstory averages						
TPH	1391	(108)	1862	(173)	2.31*	DF = 90.8
Basal area/ha (m ² ha ⁻¹)	29.19	(1.20)	26.55	(1.40)	1.43	DF = 106.3
Diameter (cm)	21.49	(0.50)	20.58	(0.70)	1.06	DF = 98.0
Height (m)	18.15	(0.36)	16.77	(0.57)	2.06	DF = 90.6
Species richness	4.91	(0.24)	5.76	(0.31)	2.19 *	DF = 102.5
Shannon's Diversity Index	1.07	(0.06)	1.35	(0.06)	3.39 ***	DF = 108.7
Evenness	0.67	(0.03)	0.55	(0.02)	3.98 ***	DF = 99.3
Seedling averages						
TPH	13153	(1621)	9649	(1058)	1.81	DF = 94.4
Site averages						
Slope (%)	10.75	(1.41)	6.55	(1.41)	2.11*	DF = 109.0
Site index	17.91	(0.39)	18.78	(0.47)	1.42	DF = 105.6
Stand age	73.21	(2.27)	69.18	(3.80)	0.91	DF = 88.5
Elevation (m)	412.17	(14.68)	401.20	(4.40)	0.72	DF = 61.3

Significance levels: *p<0.05; ** p<0.01; ***p<0.001

Nonmetric multidimensional scaling (NMS) ordination using PC-ORD version 6 (McCune and Mefford 2011) was used to compare the composition of northern hardwood forest communities between the counties in Michigan and Minnesota. NMS has relaxed normality assumptions and does not assume a linear response to environmental gradients which is common in ecological data (McCune et al. 2002). Overstory basal area per hectare by species and status (live or dead) was summarized at the plot level and used in the species or main matrix. Uncommon species were not removed. Additionally, both live and dead species were included in the ordination since they represent important structural components of the stand. Thirty-two environmental variables were used in the environmental or second matrix (appendix 2). Autopilot mode (slow and thorough) was selected using Sørensen (Bray-Curtis) distance measurement and a random starting point for both datasets. Two hundred and fifty runs were completed for both the real data and randomized data to determine dimensionality for both data sets. Chi-square analysis using Sørensen (Bray-Curtis) distance measurement was also run to explore associations between species.

RESULTS

Structural and Compositional Comparison

There were many site and structural similarities between northern hardwood forests of Minnesota and Michigan (Table 1). Northern hardwood sites in Minnesota and Michigan have on average a site index of 18 m at 50 years, a stand age of 70 years old, and an elevation of approximately 400 m. Additionally, stands have approximately 28 m² ha⁻¹ of basal area per hectare with an average diameter of 21 cm, an average height of 17 m, and thousands of seedlings (d.b.h. <2.54 cm) regenerating. One of the main differences between the states was that northern hardwood forests in Minnesota had on average significantly greater overstory density than Michigan, 1862 TPH (±173) and 1391 TPH (±108), respectively. However, there was no significant difference in the overstory basal area between the two states (Table 1). Minnesota northern hardwood stands also

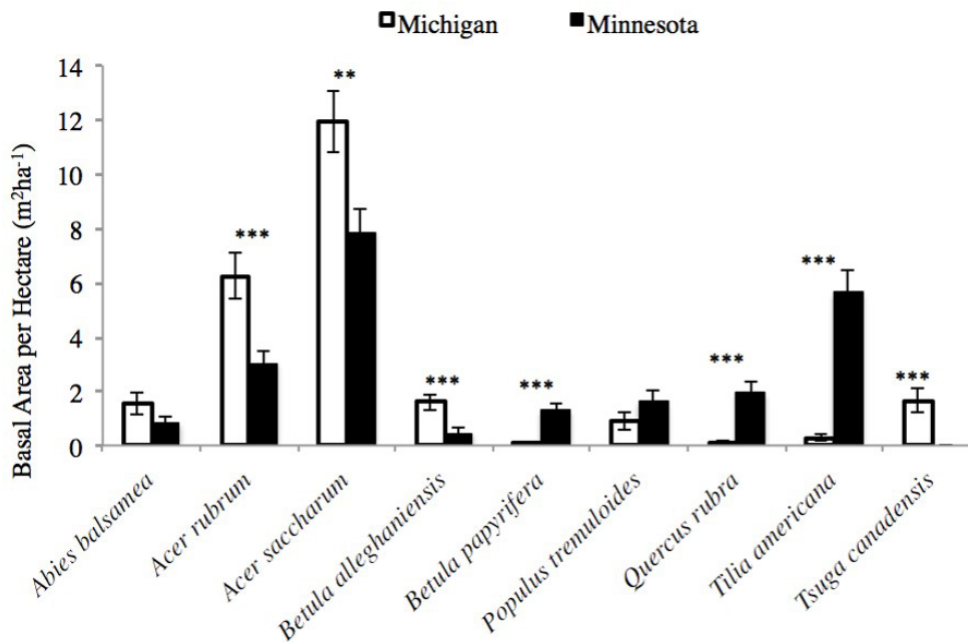


Figure 2.—Average basal area per hectare and associated standard error of the most dominant species present in Michigan and Minnesota northern hardwood forests. Student t-test with unequal variances were used to test for differences between states for each species. Levels of significance are * <0.05; ** <0.01; *** <0.001.

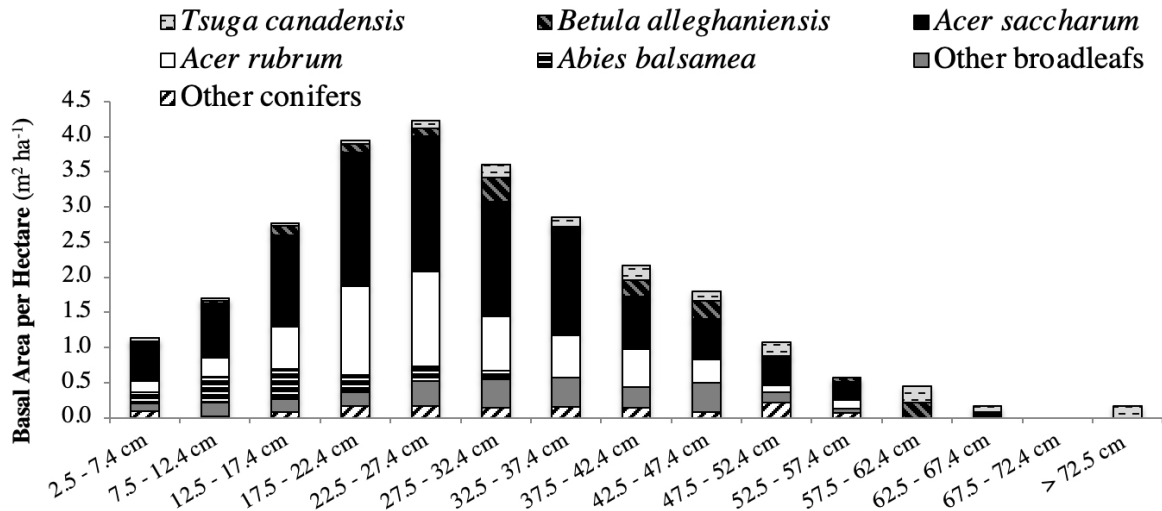
had significantly greater diversity than Michigan stands; all three measures of diversity (overstory species richness, overstory Shannon's diversity index, and overstory evenness) were significantly greater in Minnesota than Michigan (Table 1).

There were greater differences observed in the composition than the structure of northern hardwood stands in Minnesota and Michigan (Fig. 2). A total of 32 unique overstory species were observed in the 111 plots across the two states (appendix 1). Nineteen of the overstory species were common between the two states; five unique overstory tree species were observed in Michigan and eight unique overstory tree species were observed in Minnesota. Within the broader sampling area, many of the tree species had, on average, very low densities both in terms of trees per hectare and basal area per hectare. Nine species were common in Michigan and/or Minnesota: balsam fir (*Abies balsamea* (L.) Mill), red maple, sugar maple, yellow birch, trembling aspen (*Populus tremuloides* D.A. Peral), northern red oak, American basswood, and eastern hemlock. Of the nine dominant species, only two species, balsam fir and trembling aspen, were not significantly different between the two states. Red maple, sugar maple, yellow birch, and eastern hemlock all had significantly greater density in Michigan compared to Minnesota. Greater density of paper birch, northern red oak, and American basswood were observed in Minnesota compared to Michigan (Fig. 2).

Diameter Distribution

The allocation of basal area by diameter class and by species was different between the two states (Fig. 3 A, B). There was greater basal area of red maple and sugar maple across diameter classes in Michigan compared to Minnesota (Fig. 3). There was less basal area in smaller diameter classes (<17.5 cm d.b.h.) in Michigan compared to Minnesota. The Minnesota diameter distribution had a relatively flat shape with a more even distribution of basal area across diameter classes up to 42.4 cm (Fig. 3B). This is in contrast to higher basal area in larger diameter classes in Michigan; the larger diameter classes, starting at 22.5 cm, display a strong reverse-J or negative exponential distribution.

A



B

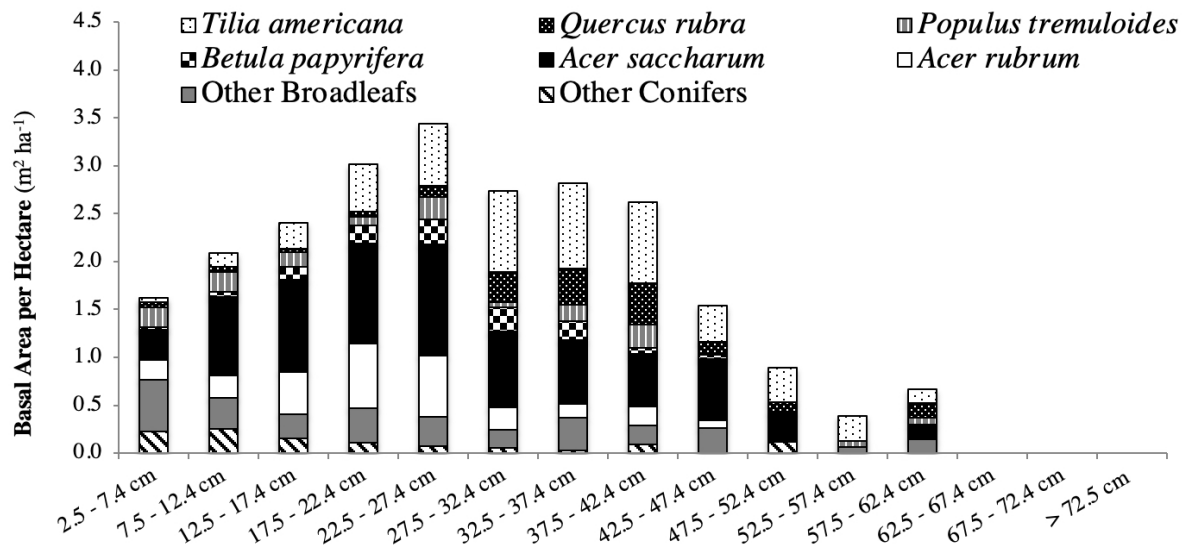


Figure 3.—Average distribution of basal area per hectare ($\text{m}^2 \text{ha}^{-1}$) by species and diameter class for northern hardwood forests in Michigan (A) and Minnesota (B) counties. Five centimeter diameter classes were used for analysis. Species with less than $1.5 \text{ m}^2 \text{ha}^{-1}$ basal area on average were grouped into one of two categories: other broadleaves or other conifers.

Nonmetric Multidimensional Scaling (NMS) Ordination

The NMS ordination resulted in a three-dimensional solution, explaining 84.7 percent of the variance in overstory community composition between Minnesota and Michigan, and had a final stress of 14.72 and final instability of 0.00 (Fig. 4). Axis 1 and axis 2 were most informative, explaining 44 percent and 25 percent of the variation, respectively. Strong separation between plots in Minnesota and Michigan was displayed in the ordination. Three environmental variables were considered important to understanding the underlying ecological gradient ($r^2 > 0.2$) on either axis 1 or axis 2. Axis 1 was associated with the plot average specific gravity of tree species present and the plot average height of overstory tree species. More negative values on axis 1 were associated with plots with higher average specific gravity and greater average height. Axis 2 was strongly associated with the longitude of overstory plots with more negative values associated with more eastern sites and more positive values associated with more western sites.

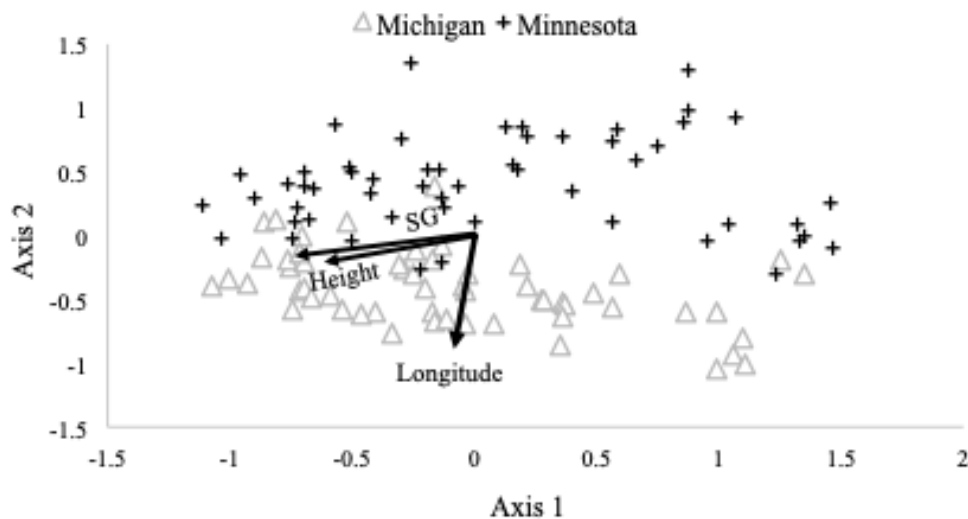


Figure 4.—Nonmetric multidimensional scaling (NMS) ordination displaying compositional differences in northern hardwood plots in Michigan and Minnesota. Axis 1 explained 44 percent of the variation, while axis 2 explained 25 percent of the variation. Plot locations and environmental variables with a $r^2 > 0.2$ are displayed in ordination space. Definitions: SG—plot average of specific gravity; Height—plot average height in meter; Longitude—“fuzzed” longitudinal values of FIA plots.

DISCUSSION

The FIA plots within northern Minnesota and the Upper Peninsula (UP) of Michigan highlight the diversity in species and structural composition that is within the northern hardwood forest type. Across the two states, 32 unique overstory species were observed including long-lived, shade-tolerant conifers, short-lived, shade-intolerant hardwoods, and the full range of silvics for other species (Burns and Honkala 1990) (appendix 1).

While this full range of species were present across the two states, there were some notable differences in terms of species composition, structure, and diversity. The NMS ordination which utilized species composition within the main matrix, resulted in pretty distinct separation in ordination space for plots from Michigan and Minnesota (Fig. 4). One of the factors contributing to differences between the two states may relate to individual species ranges and the boundaries (Burns and Honkala 1990). Minnesota represents the edge of many species ranges and may contribute to different path of stand development (Gill et al. 2016). For example, while eastern hemlock does have some very limited populations in Minnesota, this species is almost exclusively absent from Minnesota northern hardwood forests compared to the UP of Michigan where there is active research exploring management techniques related to regeneration (Webster and Lorimer 2002).

Another factor may be related to the types of silvicultural systems utilized within the northern hardwood forest types in Minnesota and Michigan. The selection system (single, group, or a combination) with natural regeneration is one of the most common and prevalent types of silvicultural systems utilized within northern hardwood forests (Nyland 1998), especially in Michigan (Pond et al. 2014). Multiple studies across the region document the ability of single tree selection with natural regeneration to generate high economics returns and the sustained recruitment of shade tolerant species (e.g., sugar maple) (Horsley et al. 2003, Neuendorff et al. 2007). There was no significant difference among ownerships within Michigan, in the implementation of single tree selection; there was a range among the ownership classes in how single tree selection utilizing the Arbogast method was implemented (Pond et al. 2014). When natural regeneration is successful, the single tree selection system results in the increased dominance of sugar maple, an aesthetically appealing stand, and the potential for high quality products (veneer quality trees) (Kiernan et al. 2008).

However, there are some notable limitations of single tree selection with natural regeneration (Walters et al. 2020). One limitation first relates to the assumption that natural regeneration will happen (Henry et al. 2021, Millington et al. 2013). Deer browse, drought, exotic earthworms, and many other factors may result in regeneration failures which may not be accounted for in single tree selection systems (Holdsworth et al. 2007, Powers and Nagel 2009). A second limitation that is increasingly being explored is the loss of overstory species diversity. For multiple decades, managers and researchers have been exploring silvicultural techniques which can increase species diversity, especially of mid- and shade-intolerant species, in maple dominated northern hardwood stands (e.g., Hupperts et al. 2020, Poznanovic et al. 2013, Shields et al. 2007).

While sugar and red maple are components of Minnesota's northern hardwood forests, they are not necessarily always the dominant species (Fig. 2). Minnesota's northern hardwood forests have greater species richness, Shannon's diversity, and evenness compared to Michigan (Table 1). Basswood, northern red oak, and paper birch all have greater overstory density in Minnesota compared to Michigan. Basswood, northern red oak, and paper birch are considered mid-tolerant or shade-intolerant species (Burns and Honkala 1990). While these species are more common in Minnesota's northern hardwood forests, there are limited examples of research studies exploring silvicultural methods to maintain or promote mixed species northern hardwood stands in Minnesota. However, there are examples in the University of Minnesota's Great Lakes Silviculture Library (GLSL) of silvicultural systems that managers are using that detail the use of larger gaps/opening through seed tree, shelterwoods systems (with or without residuals), or group selection system to regenerate mid- and shade-intolerant species (<https://silvlib.cfans.umn.edu/>). The utilization of these other regeneration harvests may in part be driven by the higher prevalence of northern red oak which is a mid-tolerant species compared to the extremely shade tolerant sugar maple (Burns and Honkala 1990)

There are numerous factors (environmental and anthropogenic) which have influenced the current species composition and structure of northern hardwood forest communities within Minnesota and Michigan. However, as climate change, invasive species, and shifting disturbance regimes influence northern hardwood forests, natural resource managers will require adaptation (D'Amato and Palik 2021). While single tree selection was considered the "gold standard" for northern hardwood management, this standard is changing and alternative methods are being explored (Huppert et al. 2020, Walters et al. 2020).

Natural resource managers will critically need to evaluate each individual northern hardwood stand and not assume natural regeneration will happen (Walters et al. 2020); natural resource managers will need to address and evaluate each of three legs of the regeneration triangle (seed source, seed bed, and environment) for each of the multiple species within a northern hardwood stand (Nyland 2006). While there is limited potential to "control" the environment, there may be opportunities to explore how residual trees, down dead wood, and different layers of vegetation may influence the local environmental conditions for regenerating seedlings. Multiple methods and techniques (salmon blading, variable radius gaps, shelterwoods with residuals, and enrichment plantings) have and are being implemented successfully to regenerate individual species, increase tree level diversity, and are documented in the GLSL. These treatments can potentially expand the "silvicultural norms" in northern hardwood management and also expand the norms for how data and results are shared through living case studies on the GLSL and within peer-reviewed literature.

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APPENDIX 1

Table 2.—Overstory tree species and presence in respective states used in the ordination from the FIA from the selected country

Species	Observed in Minnesota	Observed in Michigan
<i>Abies balsamea</i>	X	X
<i>Acer pensylvanicum</i>		X
<i>Acer rubrum</i>	X	X
<i>Acer saccharinum</i>	X	
<i>Acer saccharum</i>	X	X
<i>Acer spicatum</i>	X	X
<i>Amelanchier</i> spp.		X
<i>Betula alleghaniensis</i>	X	X
<i>Betula papyrifera</i>	X	X
<i>Carpinus caroliniana</i>	X	
<i>Carya cordiformis</i>	X	
<i>Fagus grandifolia</i>		X
<i>Fraxinus americana</i>		X
<i>Fraxinus nigra</i>	X	X
<i>Fraxinus pennsylvanica</i>	X	X
<i>Juglans cinerea</i>	X	
<i>Ostrya virginiana</i>	X	X
<i>Picea glauca</i>	X	X
<i>Picea mariana</i>	X	X
<i>Pinus banksiana</i>	X	
<i>Pinus strobus</i>	X	X
<i>Populus balsamifera</i>	X	
<i>Populus grandidentata</i>	X	X
<i>Populus tremuloides</i>	X	X
<i>Prunus serotina</i>	X	X
<i>Prunus virginiana</i>	X	
<i>Quercus macrocarpa</i>	X	
<i>Quercus rubra</i>	X	X
<i>Thuja occidentalis</i>	X	X
<i>Tilia americana</i>	X	X
<i>Tsuga canadensis</i>		X
<i>Ulmus americana</i>	X	X

APPENDIX 2

Table 3.—Environmental variables used in the ordination and the correlation with axis 1 and 2

Environmental Variable	FIA Variable Code	R ² Value Axis 1	R ² Value Axis 2
Overstory tree species richness	calculated ⁺	0.047	0.028
Overstory Shannon's Diversity	calculated ⁺	0.127	0.047
Overstory evenness	calculated ⁺	0.079	0.116
Seedling TPH	calculated ⁺	0.045	0.003
Average height (m)	calculated ⁺	0.312 *	0.042
Average crown ratio	calculated ⁺	0.015	0.007
Average diameter (cm)	calculated ⁺	0.120	0.001
TPH	calculated ⁺	0.033	0.000
Basal area/hectare (m ² ha ⁻¹)	calculated ⁺	0.104	0.137
Specific gravity	SG	0.470 *	0.032
Latitude	LAT	0.051	0.020
Longitude	LON	0.004	0.628 *
Stand Age	STAGE	0.176	0.038
Site index for the condition	SICOND	0.045	0.032
Slope	SLOPE	0.011	0.001
Aspect	ASPECT	0.014	0.000

* Strongly correlated $r^2 > 0.2$

The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

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SILVICULTURE

Alternative Silviculture Systems in Northern Hardwoods Session: Roundtable Q and A

Gary J. Roloff, Michael L. Donovan, Jason P. Hartman, Michael B. Walters, Catherine R. Henry, and Evan J. Farinosi¹

The Roundtable Questions and Answers (Q and A) followed four science-centered talks on (1) the rationale, design, and implementation of a project evaluating alternatives to selection silviculture management of northern hardwood forests, (2) preharvest vegetation structure, (3) post-harvest vegetation structure and deer browsing, and (4) pre- and post-harvest deer use. Our rationale for the followup Q and A was to highlight the critical importance of the management-research partnership in the establishment and execution of the experiment and in the development of information from the experiment that is focused on management needs. Roloff provided an overview of the Roundtable Q and A and research highlights from previous talks. This was followed by a discussion among roundtable participants and closed with a question from session coordinator Brian Huttnick (Wisconsin Department of Natural Resources).

SESSION SUMMARY AND INTRODUCTION TO ROUNDTABLE Q AND A

Roloff opened the session by citing and further developing highlights and critical points from the preceding four research talks. From Walters' project overview he pointed out two critical aspects of the project partnership: (1) research-management partnership made feasible the implementation of a large, operational scale research project sharply focused on addressing management problems, and (2) the partnerships between wildlife and forestry is critical for understanding a problem that hinges on forest-deer interactions, and for developing and implementing novel management regimes based on research results to solve the problem. From Henry's presentation, Walters emphasized the importance of making the notion of how we measure tree regeneration success for multiple forest values central to our evaluation of treatment responses. From Farinosi's talk, Roloff highlighted that some of the more aggressive, and currently little used, overstory harvesting treatments show some promise for improving tree regeneration outcomes. From Starking's talk, Roloff highlighted that tree leave tops are deterring deer movements, possibly benefitting tree regeneration. Roloff finished by saying that we've heard a lot about the science, but that it's critical to hear from the managers about what makes the project work for them.

PANEL DISCUSSION AND QUESTIONS

Mike Donovan began by stating that there is a long history of Michigan Department of Natural Resources (MDNR) being associated with research, but that it's often difficult to tie science to management directly. What is working in the alternative silviculture systems in northern

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hardwoods project is the design. He stated that he is excited by the promise for management solutions of doing a research project within their management system at an operational scale. Previously, MDNR has been associated with many research projects, but it has often been difficult to tie research results directly to management. Given that the design is directly tied to their operations, incorporates MDNR staff into research directly, and the project's scale (140 sites distributed across the northern hardwood resource), the results will have high likelihood of being adopted by management. Hartman agreed that it is a big plus that the design has brought the project into everyone's backyard (i.e., MDNR districts across the State). MDNR has previously tried similar things (i.e., research projects aimed at management problems), but it has been difficult to get momentum to change due to lack of integration with management and limited scope and scale. Hartman stated that having examples within individual management units is what's making it work. Being tied to the project in the long term, with local examples, increase the likelihood of moving the needle in making management changes. Structure is important because institutional changes in management is going to be slow.

Donovan added that the formal research-management partnerships between the Michigan Department of Natural Resources and Michigan State University (i.e., Partnerships in Ecosystem Research and Management Program) has been going on for nearly a quarter of a century and that this long-term relationship has been instrumental in establishing the level of trust required to commit time and resources to a 10+ year project, especially given that state agencies are funded on an annual basis.

Walters returned to the topic of the benefits of a multisite, broadly dispersed, operational scale design. He said that in addition to the aforementioned benefits of "examples in everyone's backyards" for institutional commitment and adoption of results, that northern hardwoods regeneration solutions (i.e., best silvicultural treatments) will likely vary across the northern hardwood forest resource due to underlying variation in site quality, stand history, deer populations, etc. Thus, successful treatments may represent local potential solutions, and give managers a "back yard" adaptive management template to further tinker. For example, over time they can modify and refine approaches that show promise both to further improving regeneration outcomes and increasing operational efficiency of novel treatments.

Following the roundtable, Brian Huttneck (Wisconsin Department of Natural Resources) asked what was on the horizon for the MSU-MDNR research-management partnership. Roloff, Hartman, and Donovan brought up the establishment of similar research in the northern white cedar resource, the desire by MDNR managers to begin a project similar to the northern hardwoods project in southern Michigan oak-hickory forests, and the recent financial commitment to years 7–12 of the northern hardwoods experiment.

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From Soup to Nuts: A Single Tree Selection Harvest from Conception to Completion

Bradley M. Hutnik¹

Abstract.—Throughout the range of the northern hardwood cover type, single tree selection is one of the most commonly prescribed natural regeneration systems. Unfortunately, being a common prescription does not necessarily mean that it is commonly implemented properly. This paper provides a case study for single tree selection management as implemented by Wisconsin Department of Natural Resources Foresters in northern Wisconsin. It reviews stand assessment, prescription writing, marking guide development, and timber marking. This case study also examines lessons learned. These lessons learned include a general lack of familiarity with the tenets of single tree selection. They also include a lack of consensus about what acceptable growing stock (AGS) means for saplings and non-sawtimber size class trees.

INTRODUCTION

Single tree selection has the unique distinction of being both one of the most widely prescribed and most misunderstood northern hardwood natural regeneration systems in the Lake States (Pond et al. 2014). As a silvicultural method, it is designed to regenerate and maintain uneven-aged stands by consistently removing trees in all size classes throughout the stand at regular intervals. Single tree selection stands are maintained at each stand entry by establishing or releasing new age classes, tending trees to develop desirable growing stock, and harvesting mature trees to reallocate growing space to new age classes (Nyland et al. 2016). In practice, it is often confused with intermediate thinning or simply the marking of individual trees. While this may seem innocuous, the potential consequences may include stand growth rates which do not meet expectations, diminished yield due to low residual stocking (cutting too heavily), and compromised regeneration due to insufficient disturbance (cutting too lightly) (Pond et al. 2014). More recently, forest managers have begun to explore other silvicultural methods with more ecological precedent and less perceived rigidity (Seymour and Kenefic 1998). Nevertheless, properly applied single tree selection prescriptions and marking guides have utility for many landowners. This paper provides a thorough case study of a single tree selection management and walks through stand assessment, prescription writing, marking guide development, timber marking, and lessons learned along the way.

BACKGROUND

The stand utilized for this case study, HCHLWA 1, is located on the Hay Creek-Hoffman Lake Wildlife Area, Ashland County, Wisconsin. For this stand, the management goal is to maintain a relatively diverse northern hardwood stand with high vertical and horizontal structural diversity for both wildlife habitat and timber production. At project initiation, HCHLWA 1 was dominated by sugar maple (*Acer saccharum*) sawtimber and poletimber, with 76 percent of the stocking in sugar maple (Fig. 1). The forest habitat type classification for this stand is ATM (*Acer-Tsuga/Maianthemum*) / ATD (*Acer-Tsuga/Dryopteris*) (Kotar et al. 2002). The stand quadratic mean diameter was approximately 10 inches diameter at breast height (d.b.h.) with 135 ft²/acre basal

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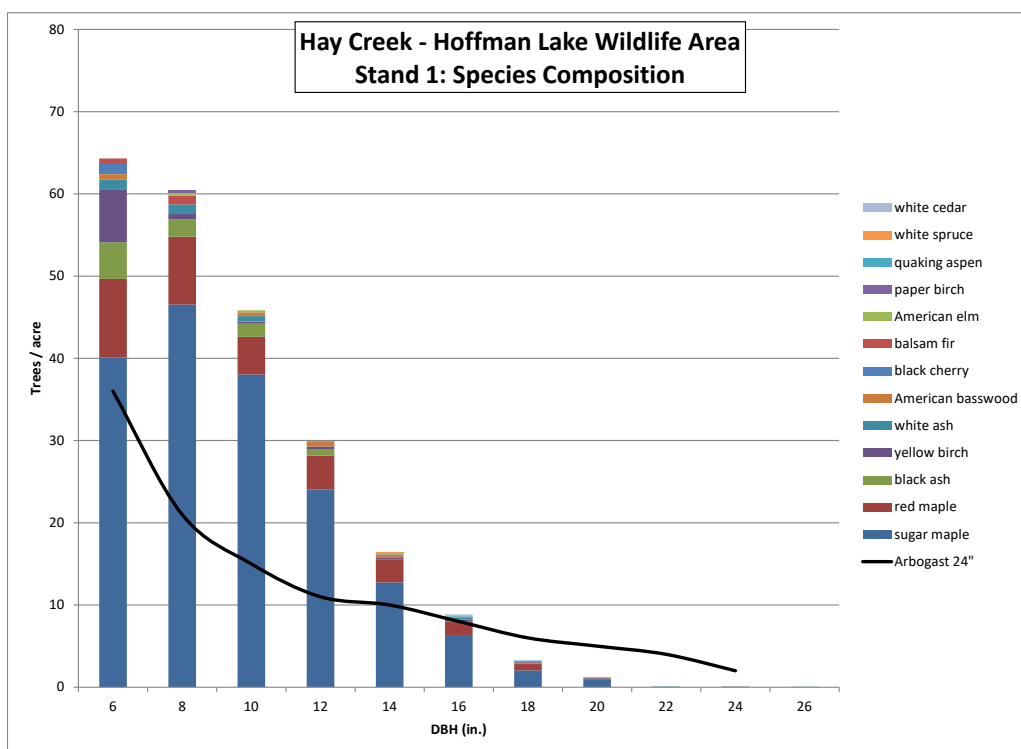


Figure 1. — HCHLWA 1 overstory species composition and diameter distribution.

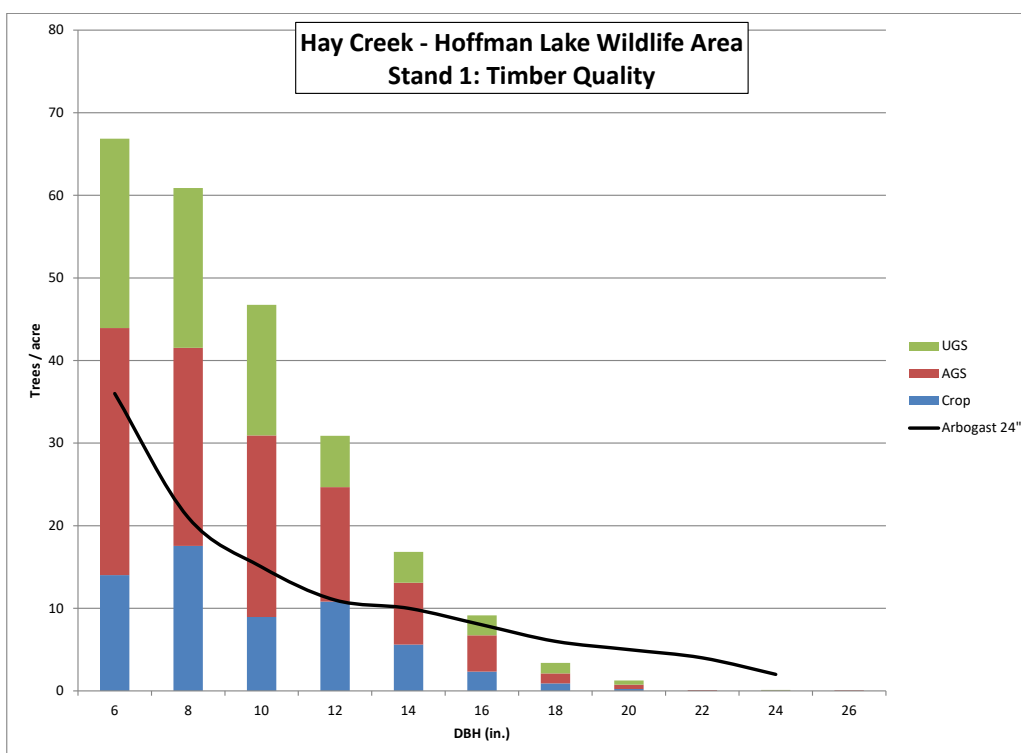


Figure 2. — HCHLWA 1 overstory growing-stock status and diameter distribution.

area. Age class diversity however was assumed to be absent. The understory was open, with sugar maple seedlings mostly less than 1 foot in height. However, where gaps occurred in the stand, sugar maple saplings were present. Overall, tree quality and potential were good with 67 percent of pole timber, 79 percent of small sawtimber, and 69 percent of large sawtimber meeting an acceptable growing-stock (AGS) status. (Fig. 2).

Table 1. — HCHLWA 1 single tree selection marking guide worksheet

	DBH	BA/tree	Current Stand		Residual Target		Tree Difference	BA Difference	Tree Cut %	Harvest Ratio	Harvest BA
			Total trees	Total BA	Target Trees	Target BA					
Poles	6	0.2	45.00	7.00	36.00	5.8	9	1.20			
	8	0.3	32.00	10.00	21.00	6.3	11	3.70			
	10	0.5	49.00	24.00	15.00	7.3	34	16.70			
Sm. Saw timber		Class Total	126.00	41.00	72.00	19.4	54	21.60	42.86%	1 out of 3	15 BA
	12	0.8	31.00	23.00	11.00	7.9	20	15.10			
	14	1.0	19.00	19.00	10.00	9.9	9	9.10			
Lg. Sawtimber		Class Total	50.00	42.00	21.00	17.8	29	24.20	58.00%	1 out of 2	20 BA
	16	1.3	12.00	16.00	8.00	10.5	4	5.50			
	18	1.7	5.00	8.00	6.00	10	-1	-2.00			
	20	2.1	1.00	2.00	5.00	10.3	-4	-8.30			
	22	2.3	0.00	0.00	4.00	10.1	-4	-10.10			
	24	3.0	0.00	0.00	2.00	6	-2	-6.00			
The Great Beyond		Class Total	18.00	26.00	25.00	46.9	-7	-20.90	-38.89%	High Risk	<5 BA
	26	3.6	0.00	0.00	0.00	0	0	0.00			
	28	4.1	0.00	0.00	0.00	0	0	0.00			
	30	4.7	0.00	0.00	0.00	0	0	0.00			
	>30	5.0	0.00	0.00	0.00	0	0	0.00			
			0.00	0.00	0.00	0	0	0.00			
			194.00	109	118.00	84.1	76	24.90	0.00%	High Risk	<5 BA

STAND ASSESSMENT

To determine if single tree selection was a suitable alternative for stand management, managers assessed stand history, site potential and operability, stand stocking and quality, stand age/structure, and regeneration as well as deer herbivory and interfering vegetation utilizing the “Checklist for Evaluating Northern Hardwood Stand Management Options²”, a tool designed to help foresters identify the full suite of management options prior to developing a silvicultural prescription. Unlike a dichotomous key, the checklist format recognizes many “right answers,” or ways to achieve a desired future condition. In application, it relies on local knowledge and professional judgement to choose the best alternatives. This assessment concluded that single tree selection was a plausible management alternative.

PRESCRIPTION AND MARKING GUIDE

Having identified single tree selection as the preferred option, the managers utilized a worksheet to identify and quantify target and actual stand conditions. In this case study, the comparison utilized four diameter size classes (Table 1). The target condition was identified using the BDq method. The target condition was:

- Residual basal area (B): 84 ft²/acre
- Maximum diameter (D): 24 inches d.b.h.
- q factor: Arbogast Curve, which consists of multiple q factors (Arbogast 1957).
- Stand re-entry: approximately 15 years

² Wisconsin Department of Natural Resources (WDNR), in press, State of Wisconsin Silviculture Handbook (2431.5).

Based on the comparison of target and actual stand conditions, the percentage of trees to be marked, the ratio of trees to be removed vs. retained, and the basal area to be removed in each size class were identified. These marking considerations, along with other marking guide elements such as leave tree priority and additional gap placement criteria were included in contract marking specifications. Contract marking and volume estimation bids varied widely, perhaps reflecting a local lack of familiarity with single tree selection marking. Bids ranged from a high of \$27,756 to the winning bid of \$12,893.

In November 2017, HCHLWA 1 was let out for timber sale bids. The harvest volume was estimated as 1870 cords of mixed species pulp, 21 MBF (thousand board feet) of sugar maple sawtimber, and 7 MBF mixed species sawtimber. The winning bid is estimated to be \$71,685. Note that this sale was on a scale basis so the actual value will reflect the recorded, not estimated, sale volume.

LESSONS LEARNED

There were several notable findings in this case study. First, most foresters associated with this study had not worked with single tree selection harvests using the BDq method. This is by no means a recent development (Filip 1977). As such, there were many questions at each step. Marking contractors were initially hesitant to employ the marking guide as it was more intensive than the single tree selection prescriptions they had used in the past. However, as they became more familiar with the marking guide, they employed it successfully. They became less worried about the multiple size class targets and complexity and started viewing them as “areas of marking emphasis.”

In addition, foresters were not used to inventorying stands to support single tree selection prescription development prior to stand marking. In addition, there were concerns that this system was not economically viable. Presale inventory does add to workloads and could be a factor in determining where or how many single tree selection harvests are employed. At least for this sale, economic viability concerns were unfounded.

Finally, a factor which garnered much discussion related to single tree selection applicability was the use of AGS trees in smaller size classes as a surrogate for true age class diversity. Foresters in the Lake States are familiar with prescriptions designed to aid in the conversion of northern hardwood stands from an even-aged to an uneven-aged condition (WDNR 2017). These even-aged to uneven-aged conversion prescriptions generally stipulate thinning from below in concert with installation of gaps. This is supported by recent work that has shown smaller diameter trees in even-aged stands do not reflect the same growth dynamics as similar trees in uneven-aged stands (Bassil et al. 2019). However, the lack of stand age data across multiple size classes hinders use of this information. Development of acceptable and unacceptable growing-stock status definitions for advance regeneration which incorporate age indicators and compliment overstory age and quality assessment may be a way forward.

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Managing for Quality Hardwoods and Multiple Age Classes

Tom Parkin¹

OVERVIEW

A selection system was applied to an uneven-aged stand consisting of mature northern hardwoods. Through group and individual selection on a 10- to 20-year cutting cycle, red maple² and sugar maple were drastically decreased in basal area to promote the growth of quality crop trees and allow greater structural diversity in the stand.

SILVICULTURE OBJECTIVE

In northern hardwood stands, Aitkin County (Minnesota) would like to increase the species diversity, reduce the abundance of sugar maple, and promote the growth of quality hardwoods, such as American basswood, northern red oak, and paper birch.

Through individual or group selection harvesting, Aitkin County would also like to maintain uneven-aged stand character with three or more age classes. The current northern hardwoods cover type will be maintained after the treatment. Promoting a multi-aged stand maximizes forest regeneration and stand quality. The stand will be tended using variable density thinning to mimic the horizontal structural diversity found in an unmanaged stand, as well as to promote the dominance of northern red oak and paper birch. In addition, snags, den trees, mast trees, and vertical stratification should be retained to provide wildlife habitat.

SILVICULTURAL PRESCRIPTION

Apply group and individual selection cuts to maintain an uneven-aged system to promote three or more age classes and release crop trees. The creation of varying gap sizes allows for regeneration of shade tolerant and intolerant species and further promote multiple age classes. With harvests occurring on cycles between 10 and 20 years, one-third of the stand basal area should be removed with each cutting cycle. Individual trees selected for harvest are marked based on risk, defect, vigor, crown competition with dominant crop trees, or release of advanced regeneration. Areas selected for group harvest are chosen based on forest inventory data and were designed to leave 20 merchantable trees per acre. Best management practices are to be followed by retaining snags, slash, and residual trees. Leaving coarse woody debris and residual trees not only increases the structural diversity of the stand, it also provides wildlife habitat and protects water resources that could be affected by harvest operations. Basal area should be primarily removed from red maple and sugar maple to decrease the abundance of these species in the stand. Black ash, paper birch, American basswood, and northern red oak must also be reduced in basal area, but at a smaller magnitude than red maple and sugar maple. The paper birch and northern red oak present are quality but represent a limited portion of the stand. In addition, advanced northern red oak regeneration is present. Therefore, group selection harvests should be used to maintain northern red oak and paper birch throughout the stand.

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² Scientific names of trees mentioned in this paper are listed in Table 1.

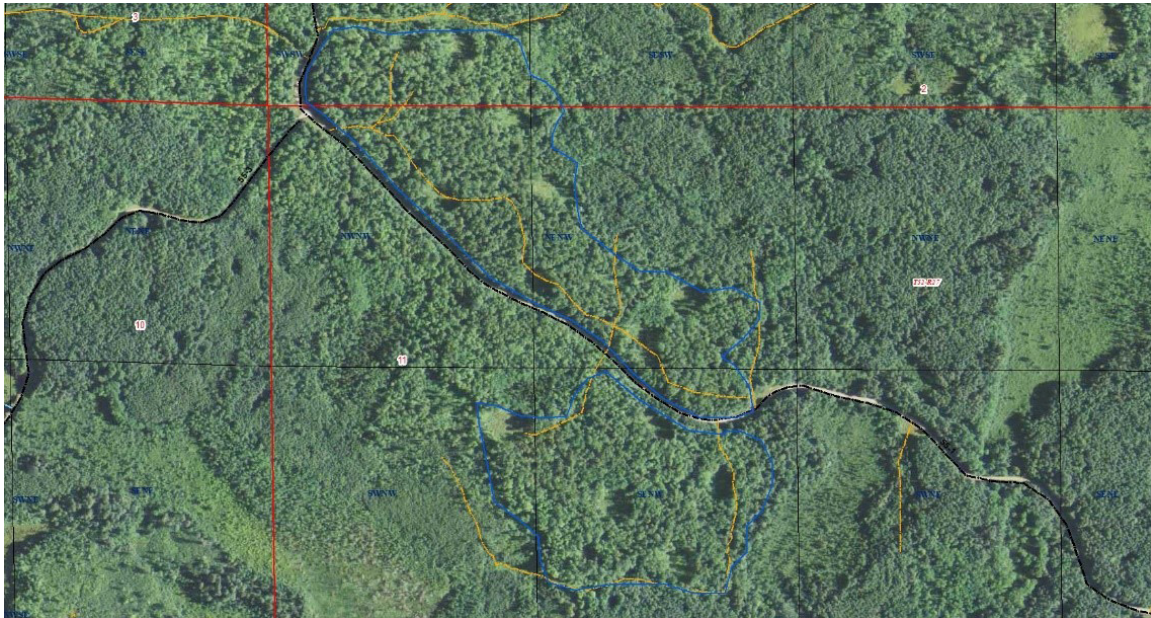


Figure 1.—Aerial view of harvest-created canopy gaps and residual stands after harvest.

TREATMENT

During the winter of 2010–2011, using group selection harvesting, trees were removed from 10 “holes,” or gaps, that ranged from a 0.5 acre to 1 acre (Fig. 1). These holes together added up to about 23 percent of the stand. During this time, individual selection cutting also occurred throughout the stand. White pine (*Pinus strobus*) stumps were found throughout the stand from previous logging operations, so it would be beneficial to plant white pine saplings in shaded portions of the stand to restore their presence.

Minnesota’s forest management guidelines (FMGs) were applied and included snags, slash, and residual trees being left throughout the stand to maintain structural diversity and sufficient wildlife habitat. Adequate access was left to allow for planting and bud capping (browse protection) in the future.

Total basal area was reduced from 128 ft²/acre to 85 ft²/acre, leaving 66.4 percent residual basal area, consistent with the prescription to remove about one-third of the basal area in each treatment. The species that experienced the greatest decrease in basal area were red maple and sugar maple, from 11 ft²/acre to 5 ft²/acre and 25 ft²/acre to 12 ft²/acre, respectively. In addition, the basal area for basswood was reduced from 76 ft²/acre to 59 ft²/acre. A total of 457 cords were extracted during the harvest. Mixed hardwood made up a large portion of that with 389 cords removed. The stand will be reassessed in 10 years to determine the need for variable density thinning, as well as to monitor the status of stand growth, health, and wildlife use.

Table 1.—Average regeneration 2 years (2013) and 5 years (2016) after cutting

Species	Scientific name	2-year regeneration trees/acre	5-year regeneration trees/acre
Northern red oak	<i>Quercus rubra</i>	406	864
Sugar maple	<i>Acer saccharum</i>	1560	2822
Paper birch	<i>Betula papyrifera</i>	84	312
Basswood	<i>Tilia americana</i>	34	312
Aspen	<i>Populus</i> spp.	425	218
Ash	<i>Fraxinus</i> spp.	17	17
Red maple	<i>Acer rubrum</i>	50	0

POST-TREATMENT ASSESSMENT

Regeneration was assessed 2 and 5 years after harvest (Table 1).

SUMMARY

A selection system was applied to 65 acres of an uneven-aged stand of mature northern hardwoods in Aitkin County, Minnesota. The management goals involve maintaining a multi-aged system for structural diversity and promoting the growth of quality crop trees. Harvests are to occur on cutting cycles of 10 to 20 years, with the stand harvested using both single tree and group selection. Harvests are to be focused on decreasing the basal area of red maple and sugar maple throughout the stand. Between cutting cycles, variable density thinning is recommended to maintain the growth of northern red oak and paper birch.

Maintaining a multi-aged hardwood stand promotes ecological resilience against climate change and protects wildlife habitat, while also generating revenue from harvesting quality crop trees. Climate change is introducing new pathogens, diseases, migrating species, and shifting habitat ranges. By promoting multiple species in multiple age classes, the impacts of these shifting variables on an ecosystem can be reduced. Multi-aged silviculture systems deal with the uncertainty of climate change by providing a short- and long-term strategy that allows for gradual adaptive adjustments to the changing environment. Multi-aged systems help to sustain ecological integrity, which leads to accommodating change rather than resisting it, as that can bring about a rapid transition that leaves the ecosystem unable to returned to desired conditions. The additional management to remove unhealthy trees and maintain a desirable density will help to increase the viability of the residual trees as well.

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Northern Hardwood Regeneration Every Forester Wants: A 33-Year Case Study

Matt Schultz¹

THE STAND: ASHLAND COUNTY FOREST COMPARTMENT 24, STAND 12

The stand is located approximately ¼ mile north of a residential area surrounding Augustine Lake in northern Wisconsin. The surrounding area is a mix of county owned forest and private forest land.

This stand underwent a single tree selection harvest in 1986 and again in the summers of 2006 and 2007. The stand is 138 acres and the primary forest type is northern hardwood (large sawlog size class [15+ inches d.b.h.], medium density [71–110 ft²/ac]), and the dominant overstory species are sugar maple² and basswood; yellow birch only accounts for 2 percent of the overstory. In 1986 the selection harvest reduced stand basal area from 135 ft²/acre to 85 ft²/acre. In 2004, the stand's basal area was 138 ft²/acre, and notes indicate heavy browse of dense sugar maple regeneration, and that marking needed to occur leaf-off due to the dense understory of sugar maple. After harvest, stand density was reduced to a residual basal area of 68 ft²/acre. Canopy gaps were created as opportunities were presented by marking several large nearby trees. The decision to reduce the stand's density lower than the standard 84 ft²/acre was largely based off an overstory that showed decline and was of fair to average quality. The habitat type is *Acer saccharum*-*Tsuga canadensis*/*Dryopteris spinulosa* (ATD).

Deer management unit deer densities from 2004 to 2013 averaged 15.6 deer/mi². The highest densities occurred in 2007 (20 deer/mi²) while the lowest occurred in 2013 (8 deer/mi²). Historical deer densities were similar ranging from 7 deer/mi² in 1983 to 19 deer/mi² in 1989, averaging 14 deer/mi² from 1983 to 1993. These data were based on old deer management unit 28; 2013 was the last year that data were calculated before the use of county units.

In 2006 the actual harvest was done with the use of a hot saw and tree length grapple skidding. In 2006 allowing such equipment to operate in this stand was a contentious issue among foresters working on the forest as some were of the opinion this equipment would cause too much damage. In March 2019, the stand was re-evaluated for the next harvest. We observed some interesting trends with regard to the abundance of yellow birch and sugar maple regeneration vs. ironwood and their relationship to stand density.

OBSERVATION

Excellent hardwood regeneration established in areas that were marked to an estimated residual basal area of 55 to 75 ft²/acre in 2004 (Fig. 1). Areas with an estimated basal area greater than 80 ft²/acre (80 to 110) in 2004 had very little regeneration and were dominated by ironwood and musclewood, including small canopy gaps in these areas (Fig. 2). In most stands, sedge cover averaged between 50 to 75 percent. Deer live in this stand year round as three sides of it are cedar swamp deer yards. There is browse, but it is not a limiting factor based on abundance of

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² Scientific names of tree species are in Table 1.



Figure 1.—Canopy gap regeneration. Basal area 55 to 75 ft²/acre. Courtesy photo by Matt Schultz, used with permission.



Figure 2.—No canopy gap. Basal area 80 to 110 ft²/acre. Courtesy photo by Matt Schultz, used with permission.

regeneration in adjacent portions of the stand. Past browse damage is visible on many sugar maple seedlings but they have been able to grow above the deer's ability to browse and are doing well. Soil maps show the same soil type across the stand. Because of the soil disturbance caused by the tree length skidding, outstanding yellow birch and some random northern red oak regeneration established and sugar maple regeneration is everywhere. Stands with larger canopy gaps/small groups resulted in the best regeneration of all species.

Table 1. Common and scientific names of tree species listed in this paper

Species	Scientific Name
Northern red oak	<i>Quercus rubra</i>
Sugar maple	<i>Acer saccharum</i>
Yellow birch	<i>Betula alleghaniensis</i>
Basswood	<i>Tilia americana</i>
Ironwood	<i>Ostrya virginiana</i>
Musclewood	<i>Carpinus caroliniana</i>

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Comparing Fall versus Winter Shelterwood Harvests

Dennis J. Thompson¹

OVERVIEW

This project compares two northern hardwood shelterwood harvests in northern Minnesota that were logged the same year but with different variables:

1. Fall harvest versus winter harvest
2. Loamy fine sand versus fine sandy loam

SILVICULTURE OBJECTIVE AND PRETREATMENT STAND DESCRIPTION

The silvicultural objective for the project was to take two northern hardwood stands dominated by sugar maple (*Acer saccharum*) and paper birch (*Betula papyrifera*) and convert them to northern red oak (*Quercus rubra*), American basswood (*Tilia americana*), and paper birch stands through a two-step shelterwood prescription. This strategy was used successfully to regenerate both stands to mid-tolerant and somewhat intolerant species such as oak, basswood, paper birch, and yellow birch (*Betula alleghaniensis*) under a uniform shelterwood system.

Stands 1 and 2 were both 80 years old at the time of the shelterwood seed cut and had a site index of 63 feet for northern red oak. Stand 1 was 28 acres while Stand 2 encompassed 33 acres. The initial basal area of Stand 1 was 103 ft²/acre of which over 50 percent was sugar maple. Northern red oak comprised 16 percent of the stand before the first treatment. Other details of Stand 1 conditions at the time of logging are shown in Table 1.

Stand 2 had an initial basal area of 109 ft²/acre. Approximately 35 percent of the stand's basal area was comprised of sugar maple. Northern red oak made up 20 percent of the stand. Trees were selected for retention during the initial shelterwood seed cut to retain the largest and best quality trees as well as the target species (i.e., oak, birch, and basswood). Other details of Stand 2 conditions at the time of harvest are shown in Table 2.

After the initial harvest, Stand 1 had a residual basal area of 40 ft²/acre. Stand 2 had 42 ft²/acre.

Table 1.—Stand 1 conditions

Stand 1 (loamy fine sand)	
First harvest	Fall 2008
Final harvest	Winter 2016-2017
Logging conditions 2008	Dry, fall harvest
Logging system	Full tree
Acorn crop	Excellent in 2008

Table 2.—Stand 2 conditions

Stand 2 (fine sandy loam)	
First harvest	Winter 2008-2009
Final harvest	Winter 2016-2017
Logging conditions 2008	Snow covered but not frozen
Logging system	Conventional in 2008-2009
Acorn crop	Excellent in 2008

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Regeneration was then released by overstory removal when it reached the desired size and stocking. This occurred in the winter of 2016–2017. The management organization, Aitkin County Land Department, uses a “5-5 rule.” Per this rule, the “top” of the shelterwood or overstory is removed when there are 500 stems/acre of desired species that are at least 5 feet tall. This effectively converted the stands to a more desirable forest type composed of the species reserved from harvest. Retention of snags, den trees, and reserve patches were included to enhance wildlife habitat. Water quality best management practices (BMPs) were also applied to protect water resources potentially impacted by harvest operations.

POST-TREATMENT ASSESSMENT

The post-treatment assessment (Tables 3 and 4) involved sampling the number of stems per acre after the first harvest (Fig. 1). This was done in 2010 and again in 2013. Sugar maple was not counted but was present in large numbers. Sampling was done again in 2017 after the overstory “top” was removed. Sugar maple was sampled at this time along with the number of stems greater than 3 feet in height.

SUMMARY

- Both silvicultural prescriptions were a success.
- Stand 1 had better regeneration because of a combination of fall logging and lighter soils.
- In 2017, northern red oak and paper birch had significant height advantage over sugar maple. The height difference was more pronounced in Stand 1, the loamy fine sand site.
- For unknown reasons, height growth of northern red oak and paper birch were better on Stand 1, loamy fine sand.
- Winter harvest can produce adequate northern red oak and paper birch regeneration given a good acorn and seed crop.
- Shelterwood harvest is an effective method to regenerate northern red oak and paper birch under a variety of scenarios.

Table 3.—Regeneration assessment for Stand 1. Initial harvest was in winter of 2008; soil was fine sandy loam.

Tree genus or species	2010	2013	2017	Stems >3 ft	Avg. height
<i>Acer</i> sp.	Not counted	Not counted	3,437	1,625	2 ft
<i>Quercus rubra</i>	1,100	1,386	2,316	1,800	3-5 ft
<i>Betula</i> spp.	3,600	2,900	4,437	3,250	3-5 ft
<i>Tilia americana</i>	25	22	875	688	2-3 ft
<i>Fraxinus nigra</i>	30	0	0	0	2-3 ft
Total trees	4,755	4,308	11,065	7,363	

Table 4.—Regeneration assessment for Stand 2. Initial harvest was in fall of 2008; soil was loamy fine sand.

Tree genus or species	2010	2013	2017	Stems >3 ft	Avg. height
<i>Acer</i> sp.	Not counted	Not counted	4,636	2,272	2-3 ft
<i>Quercus rubra</i>	860	2,000	772	409	2-3 ft
<i>Betula</i> spp.	640	1,363	3,590	2,227	3-4 ft
<i>Tilia americana</i>	600	180	909	228	2-3 ft
<i>Fraxinus nigra</i>	136	0	590	318	2 ft
Total trees	2,236	3,543	10,497	5,454	



Figure 1.—Regeneration after initial harvest. Courtesy photo by Dennis J. Thompson, used with permission.

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Silvicultural Options for Rehabilitating High-graded Yellow Birch-conifer Stands

Patricia Raymond, Marcel Prévost, and Vincent Roy¹

Abstract.—Prior to the 1990s, diameter-limit cutting was widely used in Québec, Canada, to harvest valuable trees in hardwood-dominated temperate forests. This practice can impoverish stands in terms of volume, structure, composition, wood quality and regeneration. As a result, many high-graded stands still require rehabilitation today. This study assessed the 15-year effects of four regeneration methods combined with three scarification treatments in yellow birch–conifer stands. Cutting and scarification treatments did not increase the regeneration of desired species (birches, spruces and fir). Rather, they stimulated competition, because they were applied during a poor seed year. Stand recovery after 15 years in terms of growth, vigor and regeneration in the untreated control and the strip clearcut leave strips reflected the resilient nature of these stands. However, silviculture would be required to improve overall stand quality. An active rehabilitation strategy combining shelterwood and ground disturbance during a good seed year should help to improve stand quality and regeneration.

CONTEXT

Prior to the 1990s, hundreds of hectares of hardwood dominated stands were harvested by diameter-limit cutting in the Laurentian forest of Québec, Canada. By solely focusing on timber trees of economically valuable species, these cuts often left stands with highly variable density that were impoverished in terms of species composition and wood quality. In many cases, the lack of attention to the regenerating layer, combined with damage from a spruce budworm (*Choristoneura fumiferana*) epidemic, caused regeneration deficiencies, especially on productive sites such as those supporting yellow birch (*Betula alleghaniensis*)-conifer stands. As a result, a high proportion of stands were invaded by noncommercial species. Even though diameter-limit cutting is now banned on public land in Québec, many high-graded stands still require rehabilitation treatments to sustain timber production and ecosystem services (Power et al. 2019). In this study, we assessed the 15-year effects of silvicultural rehabilitation scenarios on stand growth, quality, vigor, and regeneration, as a first step toward ecological rehabilitation of natural stands dominated by yellow birch and conifers, a common forest type in the Laurentian forest of eastern Canada.

METHODS

Established in 2001 near La Tuque (Québec, Canada), the trial comprises four blocks comparing four regeneration methods applied on 1-ha experimental units: untreated control (left to grow; basal area 11.5 m²/ha [50.1 ft²/ac]); strip clearcutting (20-m [65.6 ft] strips); uniform shelterwood (50 seed bearers/ha, 3.5 m²/ha [20 seed bearers/ac, 15.2 ft²/ac]); and seed-tree (10 seed bearers/ha [4 seed bearers/ac]) (Fig.1) (Raymond et al. 2020). Natural regeneration monitoring units (0.5 ha [1.2 acre]) tested site preparation in subplots: no scarification, spot scarification (400 spots/ha [162 spots/acre]), and mechanical raking. Vegetation surveys were conducted in years 0, 1, 5, 10, and 15. Data were analyzed by ANOVA with repeated measurements ($\alpha = 0.05$).

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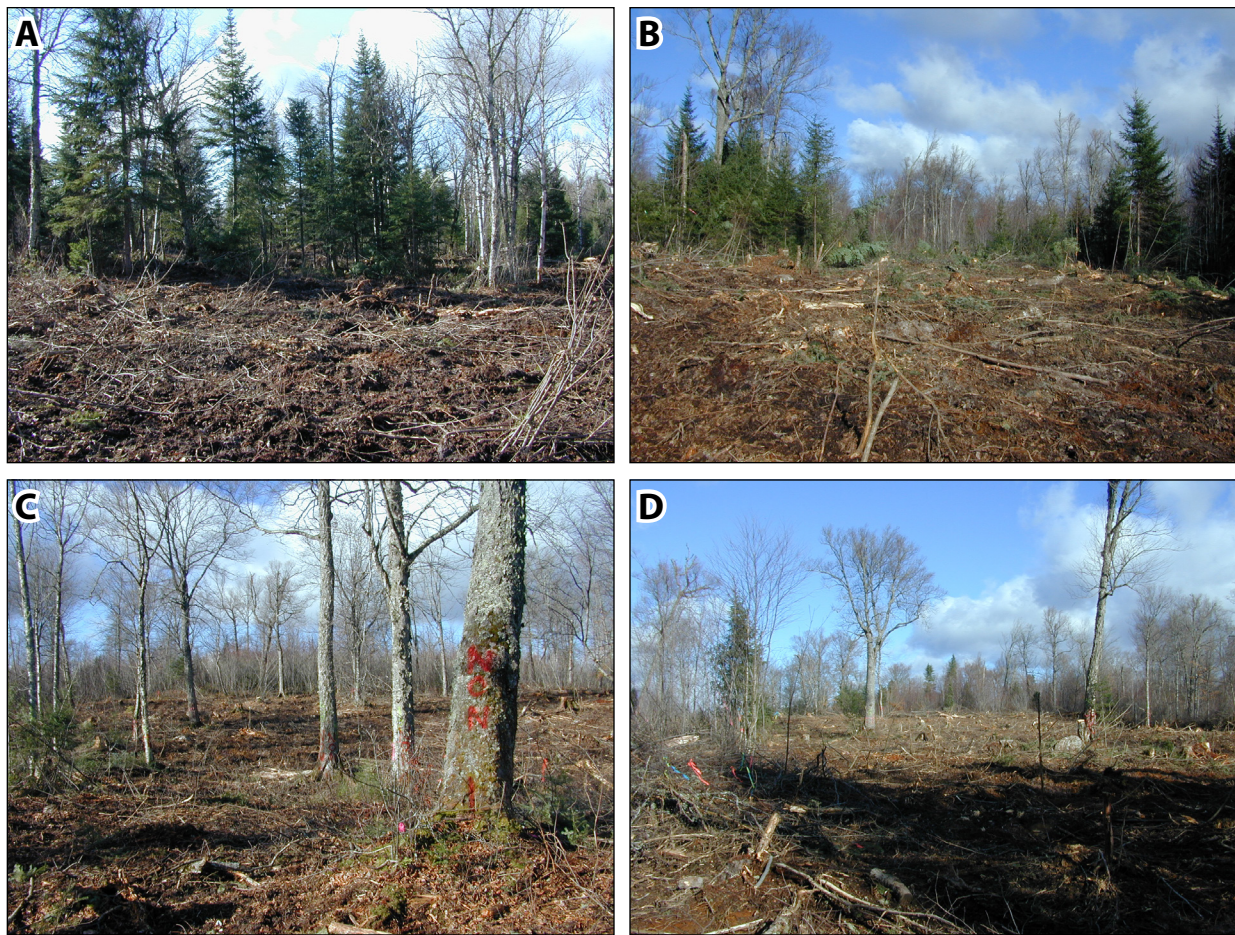


Figure 1.—We compared four regeneration methods in this rehabilitation study: (A) untreated control (left to grow; basal area 11.5 m²/ha [50.1 ft²/acre]); (B) strip clearcutting (20-m [65.6 ft] strips); (C) uniform shelterwood (50 seed bearers/ha, 3.5 m²/ha [20 seed bearers/acre, 15.2 ft²/acre]); and (D) seed-tree (10 seed bearers/ha [4 seed bearers/acre]). Courtesy photos by Vincent Roy, used with permission.

RESULTS AND DISCUSSION

Stand recovery in terms of growth, vigor, and regeneration after 15 years in the untreated control and the strip clearcutting leave strip reflected the resilient nature of these hardwood-dominated mixedwood stands (Fig. 2), with balsam fir (*Abies balsamea*), red spruce (*Picea rubens*), and white spruce (*Picea glauca*) saplings and poles contributing to the recovery of total basal area (BA) and that of acceptable growing stock (AGS; BA of vigorous trees with potential timber). The untreated control and strip clearcutting treatments, however, had high BA of unacceptable growing stock. Uniform shelterwood treatments recovered more slowly in BA and AGS but had greater BA of high quality trees (vigorous trees with potential sawlogs) than the control. Seed-tree method was less optimal because of its slow recovery and high understory competition.

The lack of synchronization with a good seed year limited the efficiency of scarification and increased the abundance of noncommercial species instead of promoting desired species (yellow birch, spruces, and balsam fir). Vegetation management constitutes one of the greatest challenges in rehabilitation silviculture, especially in a context of restricted herbicide use like in Québec (Prévost and Charette 2019). Combination of uniform shelterwood with mechanical raking could however adequately regenerate the stands. This scenario could have been more effective if conifers had been maintained in the overstory and understory strata. Spruce regeneration was marginal in terms of density and stocking, so enrichment planting is recommended to rehabilitate this component when seed bearers are scarce (Dumais et al. 2018, Hébert et al. 2013).

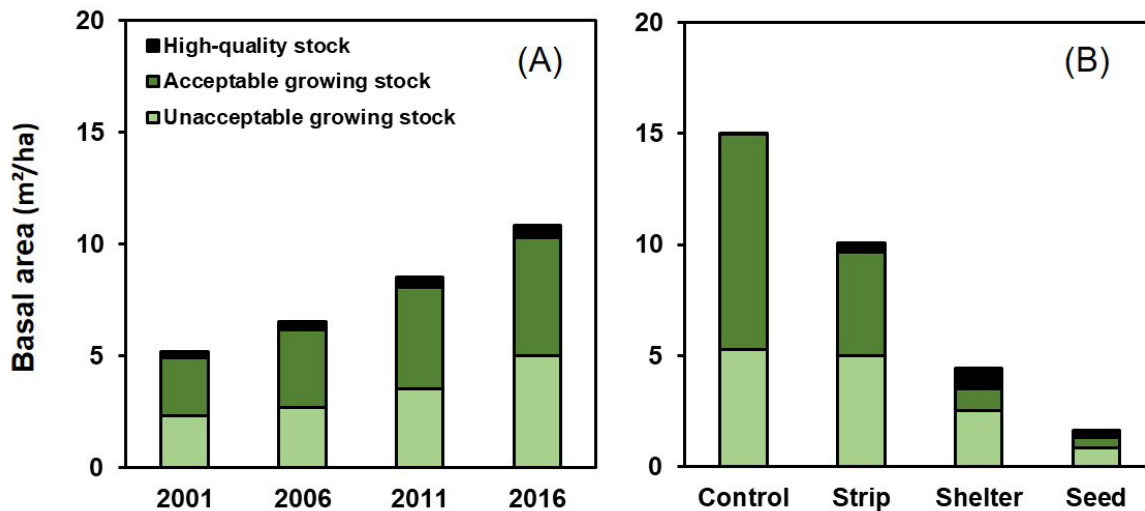


Figure 2.—Effects of year (A) and regeneration method (B) on merchantable basal area (m²/ha). Note that cumulative bars correspond to total basal area and that acceptable growing stock (AGS) includes basal area of high quality stock. Control = untreated control; Strip = strip clearcutting; Shelter = uniform shelterwood; Seed = seed-tree method.

CONCLUSION

Depending on the goal and initial conditions, a gradient of passive to active rehabilitation can be considered to restore productivity in high-graded mixedwood stands. Without treatment, total BA and AGS can recover, but some ecosystem components (e.g., companion species, deadwood, or other structural attributes) might be lacking or will recover very slowly. Active rehabilitation is required to improve stand composition, quality and structure. In these cases, shelterwood systems retaining overstory and understory conifers, combined with scarification (raking) during a good seed year, are recommended to improve stand quality and regeneration.

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Introducing the NH-SEED: A Holistic Experiment to Revisit Classical and Test Novel Silvicultural Systems in a Changing World

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Abstract.—Forest stewards aim to ensure forest sustainability through the application of the best available science. However, current silvicultural guidelines were developed under historical social, economic, and ecological conditions. When applied under novel conditions, these guidelines may have unpredictable or undesirable outcomes. Furthermore, silviculturists increasingly aim to manage ecosystems as complex adaptive systems, which requires a holistic understanding of ecosystem processes and functions. We established the Northern Hardwood Silviculture Experiment (NH-SEED) to develop alternative silvicultural systems for the management of Great Lakes northern hardwoods through identifying critical, process-limiting dynamics. This before-after, control-impact experiment uses a replicated split-plot design to investigate the influence of harvest intensity, site preparation, deer exclusion, and direct seeding. We are assessing: (1) logging productivity and impacts, (2) stand composition, structure and development, (3) financial returns, (4) understory plant community dynamics, (5) changes in wildlife populations, and (6) social impacts in response to the experimental treatments.

INTRODUCTION

Forest stewards aim to “ensure the continued health, integrity, and use of forests to benefit society in perpetuity” through the use of “our knowledge, skills and conservation ethic” (SAF 2000). This requires the application of the best available science to resolve ecological, social, and economic challenges. Nevertheless, while current silvicultural recommendations may represent the best available science, the outcomes of disturbances, such as silvicultural treatments, are influenced by ecological memories of initial or historical states (Johnstone et al. 2016, Webster et al. 2018), which were formed under often different social, economic, and ecological conditions than exist today and into the future. Therefore, when applied under novel conditions they may result in unpredictable, or worse still, undesirable outcomes. For example, many of the pre-existing, long-term, silvicultural studies initially focused on the issues that were important at the time, primarily wood production, quality development, and regeneration (Lugo et al. 2006). In the maple-beech-birch (*Acer-Fagus-Betula*) dominated northern hardwoods of North America, silvicultural research began in 1923 with the establishment of the Dukes Experimental Forest (Kern et al. 2014), and work undertaken by Eyre and Zillgitt (1953). In spite of applying the best available science at the time (Arbogast 1957), a potential negative result for biodiversity and forest resilience in the face of climate change (Elmqvist et al. 2003, Mori et al. 2013) has been “maple-ization” of northern hardwood stands over time (Angers et al. 2005, Crow et al. 2002, Doyon et al. 2005, Neuendorff et al. 2007, Schulte et al. 2007).

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In light of these challenges, we established a novel, long-term silvicultural study at Michigan Technological University's Ford Forest in the Upper Peninsula of Michigan. The overall goal of the Northern Hardwood Silviculture Experiment to Enhance Diversity (NH-SEED) is "to develop a sustainable plant production system for the production of timber from northern hardwood forests in the north central region which maintains a diversity of tree species for timber production, wildlife habitat, and ecological resilience" through identifying critical, process-limiting dynamics and potential management solutions. The experiment uses a before-after, control-impact (BACI) design, with a replicated split-plot design to investigate potential impacts of light limitation, seedbed limitations, deer browse, and seed limitation on diversity of forest regeneration and recruitment through the application of gradients of harvest intensity, site preparation, deer exclusion, and direct seeding. In addition, this experimental design provides opportunities for a variety of research topics that together provide a holistic framework for investigation including: (1) logging productivity and impacts, (2) stand composition, structure, and development, (3) financial returns, (4) understory plant community dynamics, (5) changes in wildlife assemblages and population viability of vulnerable wildlife populations, and (6) landowner willingness to implement the various silvicultural treatments.

Specific outcomes from each of these research topics are addressed separately by presenters in this organized session, with an extended abstract or manuscript for each.

DESIGN AND IMPLEMENTATION OF NH-SEED

Study Site

NH-SEED occupies 111 acres within Michigan Technological University's Ford Forest near Alberta, MI. At the time of European settlement, this area of the Ford Forest was dominated by sugar maple (*Acer saccharum*)/yellow birch (*Betula alleghaniensis*) forest; however, harvesting shortly after European settlement removed many large white pines (*Pinus strobus*), with scattered remnant well decayed stumps still present. In the mid-20th century, the forest was managed by Ford Motor Company primarily for hardwood timber. Since the 1950s, the forest has been managed by Michigan Technological University and is utilized for research and teaching. The NH-SEED site has been actively managed during Michigan Technological University's tenure using single-tree selection on a 10- to 15-year cutting cycle, until the establishment of the experiment in 2017.

The topography is rolling, and the mesic, moderately rich soils are dominated by well drained Champion cobbly silt loams with inclusions of poorly drained very stony Witbeck, and Carbondale and Tacoosh mucks (NRCS 2019). The habitat type is *Acer saccharum*-*Tsuga canadensis*/*Dryopteris spinulosa* (ATD), with a predominantly windthrow disturbance regime and relatively long return intervals (Burger and Kotar 2003). Prior to establishing the experiment, the stand had a basal area of 86.1 ft²/acre, of which 68.6 ft²/acre was sugar maple. The stand was fully stocked with a stand density index of 158, relative density of 93 percent (Tubbs 1977), and a broadly reversed-J size-class distribution, with few trees larger than 22 inches.

Experimental Design

Foundational work to establish NH-SEED began in mid 2015, with the initial pretreatment vegetation data collected during 2016. The experiment uses a replicated split-plot design, with every combination of levels within four factors represented in three replicate blocks. While laying out the experiment, efforts were made to ensure each replicate block was contiguous and as homogeneous as possible, using topographic breaks and roads as boundaries wherever possible.

Each of the three replicate blocks is divided into six silvicultural systems (six levels): clearcut (CC), single-tree selection (STS), shelterwood with high canopy cover (SW-H), shelterwood with low canopy cover (SW-L), irregular shelterwood with high canopy cover (ISW-H), and irregular shelterwood with low canopy cover (ISW-L). Each silvicultural system treatment unit occupies approximately 6 acres. The STS silvicultural system represents the business-as-usual approach and is therefore considered to be a control treatment for this factor. Three levels of site preparation are applied to each of the six silvicultural systems, including: untreated control, scarification, and artificial tip-up mounds. Each site preparation treatment unit occupies approximately 2 acres. Further, each site preparation treatment includes a deer exclosure (two levels, i.e., inside and outside exclosure), with seed addition plots both inside and outside the exclosure (two levels, i.e., with and without seed addition). Each deer exclosure was 400 ft², and each seed addition plot was 200 ft². In total there are 72 factorial treatment combinations represented on each of the three replicates.

The silvicultural systems included in the experiment encompass a wide gradient of management approaches. The CC silvicultural system removed all trees >4.5 feet tall in a single harvest with an estimated rotation length of 120 years. In contrast, STS silvicultural system aims to regularly harvest a sustainable volume on a 15-year cycle by maintaining a reverse-J shaped size class distribution using regulation with 75 ft²/acre basal area in trees ≥5 inches d.b.h., Q-factor of 1.3 and maximum diameter at breast height (d.b.h.) of 20 inches. Both SW-H and SW-L aim to regenerate the stand through two harvests. The first harvest removes small trees to release growing resources and promote the establishment of regeneration. SW-H aimed to leave 60 percent residual canopy cover by removing all trees less than 10 inches. In contrast, SW-L aimed to leave just 30 percent canopy cover by removing all trees less than 14 inches. The second harvest is planned for approximately 2024 and will remove the remaining overstory of predominantly large diameter trees to promote the growth of the established regeneration. Currently, the shelterwood (SW-H and SW-L) and irregular shelterwood (ISW-H and ISW-L) silvicultural systems are identical; however, the overstory will not be removed in the irregular shelterwoods resulting in a two-aged stand for an extended period. The silvicultural systems were established with an initial commercial harvest during February and March 2017. All harvesting aimed to remove sugar maple, while preferentially retaining minor species. Furthermore, all conifers were retained.

This harvest was followed up by a silvicultural cleaning to remove all nonmerchantable small diameter trees (>4.5 ft tall and <4 inches d.b.h.) from all shelterwood, irregular shelterwood, and clearcut treatment units in August 2017. In contrast, these small trees were not removed from STS as they are intended as advance regeneration and their presence is fundamental to this management approach.

The artificial tip-up mound site preparation treatment was applied during the initial commercial harvest. Approximately 30 trees/acre were designated to be tipped-up while harvested by wrenching the tree from the ground with the mechanical felling head before cutting the trunk into logs. While we originally aimed to tip up the largest harvested trees, concern for damaging machines that are not designed for such use compelled us to target somewhat smaller diameter trees. Post-harvest inventory indicated that on average 34 mounds/acre (± 1.9, 1 SE) were created, with a mean mound width of 53.9 inches (± 3.8, 1 SE), and pit depth of 5.7 inches (± 1.1, 1 SE) and width of 59.3 inches (± 4.3, 1 SE). The scarification treatment was applied using a small dozer with salmon blade in October 2017, with the aim of disturbing the soil surface and removing competition vegetation on approximately 50 percent of the treatment unit. Fifty-four deer exclosures were erected during the summer of 2017 and spring 2018. Finally, a mix of native tree seeds were broadcast seeded on subplots between June and November of 2018, according to the natural dispersal timing of each species. Seed was added at the prescribed rate suggested by silvicultural recommendations if available, or at the high end of natural dispersal rates reported in the literature.

CONCLUSION

Modern, long-term silvicultural experiments are necessary to understand how silvicultural systems applied within the context of current forest and environmental conditions affect ecological, social, and economic outcomes and processes through time. While this experiment has and continues to yield important insights, the greatest value of this study likely rests on subsequent inquiries that leverage its solid conceptual and experimental foundation.

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An Assessment of Eastern Hemlock Crown Dynamics 10-years After Thinning on the Allegheny Plateau, Pennsylvania

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Abstract.—Hemlock woolly adelgid (HWA) threatens the existence of eastern hemlock trees and associated ecosystems. We propose that increasing canopy light exposure via silvicultural thinning can reduce hemlock's vulnerability to HWA. Four, overstocked stands on the Allegheny National Forest were selected for thinning. There was no HWA infestation and half of each stand was thinned. Thirty circular plots per stand were established surrounding a hemlock targeted for crown release on 3 to 4 sides. Similar criteria were used to select hemlocks in 30 untreated plots. We visited subject trees prethinning, and 5 and 10 years post thinning; diameter, total height, live crown ratio, and crown area were measured on 246 trees. Temporal changes in diameter were not significant between treatments but trees in thinned plots averaged 5 cm larger after 10 years. Live crown ratio was maintained in thinned stands and decreased after year 5 in controls. Crown area increased in thinned plots and decreased in controls.

INTRODUCTION

Eastern hemlock (*Tsuga canadensis* (L.) Carr.) is distributed from the southern Appalachian Mountains to southeastern Canada and westward to the central Lake States (McWilliams and Schmidt 2000). It is a long-lived, shade-tolerant conifer occurring in pure and mixed stands across a range of primarily mesic sites (Godman and Lancaster 1990). Because hemlock stands contribute unique structural and functional landscape attributes, hemlock is considered a foundation species with a specific role in ecosystem processes (Ellison et al. 2005). Hemlock's shade tolerance and slow growth habit result in dense, multi-layered canopies (Fajvan and Seymour 1993), important to terrestrial and aquatic wildlife habitat (Snyder et al. 2002, Tingley et al. 2002, Witt and Webster 2010).

The hemlock woolly adelgid, (HWA, *Adelges tsugae* Annand) is a major threat to forest ecosystem health and economic viability of eastern North American hemlock species—eastern hemlock and Carolina hemlock (*Tsuga caroliniana* Engelm.) (Knauer et al. 2002). Since its introduction in the 1950s, HWA has spread approximately 5 to 20 miles/ year (Evans and Gregoire 2007, Morin et al. 2009), infesting hemlock throughout most of its range (USDA Forest Service 2019). Wide-ranging hemlock decline/mortality rates suggest that tree health, stand structure, and site variables influence hemlock's vulnerability to HWA feeding (Pontius et al. 2002, Rentch et al. 2009). Hemlock in dominant and codominant overstory crown class positions appear to survive HWA longer than intermediate and overtopped crown class trees (Eschtruth et al. 2006, Onken 1996, Orwig and Foster 1998). Tree crown variables are also more likely to reliably predict the degree of hemlock decline after infestation. The effects of HWA on the rate of hemlock-growth decline and mortality have been correlated with crown class and live-crown ratio (Rentch et al. 2009). Infested hemlocks with crowns receiving full sunlight, such as those growing along forest edges or

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in gaps, appear to survive longer than trees growing in shade. Higher light (Brantley et al. 2017, Hickin and Preisser 2015, Lapham et al. 2018) and temperature (Sussky and Elkinton 2015) may negatively affect HWA survival and promote new shoot growth (Ford Miniati et al. 2020, McAvoy et al. 2017).

Silvicultural manipulations that reduce stand density alter forest climate and soil and foliar nutrient cycles (Van Cleve and Zasada 1976). Thinnings reallocate fixed resources among fewer stems increasing the amount of light, water, and nutrients per tree and enhancing growth. Foliar quantity is affected because of modifications to branch size–foliage weight relationship and the number and (or) size of branches within the crown (Gillespie et al. 1994). Increasing crown size could improve a tree’s ability to deal with stressors including insect attack (Fajvan 2008, Knauer et al. 2002, Waring and Pitman 1985).

The effectiveness of silvicultural treatments for improving resource acquisition and tree health in mixed-species hemlock stands has not been extensively studied. There are few thinning studies in mixed-hemlock stands containing a significant hemlock component (>30 percent basal area) (Fajvan 2008), that focus on reducing stand density specifically to favor hemlock growth. Hemlock height and diameter growth after crown release is related to preharvest stand density and canopy status (overstory vs. understory) (Marshall 1927, Merrill and Hawley 1924). Trees growing in dense stands showed 60 percent greater growth after thinning (from above and below) than stands that were understocked. Hemlocks previously growing in suppressed canopy positions tend to have better stem form and faster growth after release than open-grown associates of similar size. Age appears to be a minor factor in hemlock growth response; older trees typically grow better than younger ones unless prolonged suppression (>60 years) has significantly reduced crown area (Fajvan and Seymour 1993, Marshall 1927).

Relationships of HWA Biology with Hemlock Physiology

HWA’s complex reproductive cycle produces two asexual generations per year: the spring “progrediens,” and overwintering “sistens,” which take advantage of hemlock’s winter physiological activity. In both generations, first instar “crawlers” settle on twigs, insert their stylets into the underside of the needle base, and feed on nutrients stored in xylem ray parenchyma cells (Havill et al. 2014, Young et al. 1995). The prolonged winter feeding of the sistens generation allows it to tap into a tree’s stored food in the absence of any potential predators. The xylem ray parenchyma cells play an important functional role in transpiration solute and carbohydrate storage, and transport and storing of water reserves. HWA-caused carbohydrate depletion from these cells can impact both carbon and water cycling and may be most apparent in trees that already have a marginal carbon balance (Secchi et al. 2017), such as hemlocks in intermediate crown class positions (Rentch et al. 2009).

High densities of HWA deplete food reserves and diminish a tree’s ability to produce new foliage (Evans 2002). HWA is chronic in nature and effects are not immediate. Trees with low HWA populations tend to have larger percentages of nymphs in the upper crown whereas heavily infested trees have more nymphs in the lower crown (Evans and Gregoire 2007). Subsequent needle discoloration, premature needle drop, branch tip dieback, and foliage thinning causes growth decline (Rentch et al. 2009) and can result in tree mortality ranging from almost none to 95 percent (Bair 2002, Mayer et al. 2002, Orwig and Foster 1998). Stand-level mortality can occur quickly and uniformly, especially in the presence of other stressors or can occur slowly and in patches for more than a decade.

Use of Silvicultural Thinning in HWA Management

Scientific and anecdotal evidence suggests that while healthy hemlocks are not less susceptible to HWA attack, they do have a better chance of surviving longer than trees stressed by crowded conditions and shading (McClure 1995, Sivaramakrishnan and Berlyn 2000) possibly due to environmental conditions less suitable for HWA survival (Brantley et al. 2017). Maintenance of healthy trees through thinning has been proposed as part of an integrated strategy combined with chemical and biological HWA controls (Mayfield et al. 2015).

We initiated a study in 2005 to determine if stand structure manipulations can be used ahead of the leading edge of HWA invasion to improve individual host tree and stand resistance. Specifically, we designed thinnings to reduce relative stand density in fully stocked and overstocked hemlock-hardwood stands (Lancaster 1985) to reallocate site resources and enhance the health of the remaining hemlocks (Fajvan 2008).

Our original study objective was to determine whether thinning hemlock-hardwood stands would improve or maintain hemlock health and increase live crown ratio (LCR), crown area (CRAREA), and diameter prior to HWA arrival. Four Pennsylvania stands were thinned in 2007 and have been monitored for 10 years however, there has been no HWA infestation to date. In this paper we present the findings from the intensive monitoring of crown attributes for 246 “subject” trees, half of which received direct crown release on 3 or 4 sides in thinned plots. We compare the changes in growth parameters between trees with released crowns and those without.

METHODS

Study Area and Treatment

Thinnings were conducted in four, 24-ha stands selected on the Allegheny National Forest (ANF) in northwestern Pennsylvania near the town of Warren (41.64976°N, 79.03913°W). The forest covers about 210,000 ha and is 90 percent forested with an average elevation of 427 m. Soils in the project area belong to two main soil groups: Cavode silt loams with 0 to 8 percent slope, and Cookport very stony silt loams, with 0 to 15 percent slope. Vegetation consists of second-growth, 70- to 100-year-old mixed Allegheny hardwood species, dominated by black cherry (*Prunus serotina* Ehrh.), red maple (*Acer rubrum* L.), black birch (*Betula lenta* L.), yellow birch (*Betula alleghaniensis* Britt.), northern red oak (*Quercus rubra* L.), sugar maple (*Acer saccharum* Marsh), and American beech (*Fagus grandifolia* Ehrh.). Hemlock is found either in pure patches or dispersed within the hardwoods. The ANF has a moderate climate, with warm and humid summers. Average temperatures range from 23.9 to 26.7 °C (75 to 80 °F) in summer to -3.9 to -6.7 °C (20 to 25 °F) in winter and mean annual precipitation ranges from 889 to 1,295 mm (USDA Forest Service 2018). All stands were located on the ANF Bradford Ranger District; three in compartment 301 and one in compartment 341.

Stand size was determined based on feasibility of conducting a commercial harvest. Required hemlock content was a minimum basal area of 7 m²/ha. The three stands in compartment 301 were overstocked with total basal areas ranging from 39 to 46 m²/ha. These stands were further distinguished based on the overstory dominance of either black cherry, or red oak and red maple. Hemlock content ranged from 11.5 to 16 m²/ha in the black cherry-dominated stands (Stands 1, 2) and from 7 to 11.5 m²/ha in the oak-red maple – dominated stand (Stand 3). Stand 4 was fully stocked at 23 m²/ha with 8 m² ha⁻¹ hemlock and 33 percent of hemlock stems <13 cm d.b.h. (diameter at 1.37 m above ground). The overstory was composed of red maple, black birch, and

American beech. Clumps of noncommercial sized hemlocks were thinned with brush saws and left on site in Stand 4.

The only published silvicultural thinning guidelines for hemlock-hardwood stands are based on data from New England and the Lake States (Lancaster 1985, Tubbs 1977). We followed the stocking targets of the New England guidelines, which recommended removal of at least 6 to 7 m²/ha of basal area; however, if stands are very dense (>46 m²/ha), basal area removal should not exceed more than one-third of the total in any given operation (Lancaster 1985).

In 2005, prior to timber marking, six 4-ha treatment blocks were established in each stand. Three of the treatment blocks were then randomly assigned to be thinned. Marking guidelines were designed specific to each stand's structural characteristics, recent ANF inventory data, and stocking guidelines with the general goal to reduce relative stand density 30 to 40 percent (Lancaster 1985). The treatment is primarily a crown thinning to reduce crown competition however, low thinning (Smith et al. 1997) criteria were also incorporated, especially in the compartment 341 stand, to address the spatial and structural variability of hemlock stems. In some instances, hardwood trees were removed because they were overtopping hemlocks with good stem form and LCR >30 percent. In dense hemlock clusters trees with <30 percent LCR, which are less likely to respond to the treatment (Marshall 1927, Smith et al. 1997), were targeted for removal.

After marking, ten 0.04-ha circular vegetation sample plots were located in each treatment block according to a systematic random procedure wherein each block was roughly divided into ten 0.4-ha sections and one sample plot randomly located within each section. In the blocks designated for thinning, a residual hemlock tree that was targeted for canopy release (e.g., has three to four surrounding stems marked for removal), served as the plot center. The center trees are referred to as "subject" trees. Similar selection criteria were used to identify 10 hemlocks to serve as subject trees in the untreated blocks totaling 60 per stand. Commercial thinnings were conducted in winter and spring 2007.

Vegetation Sampling

All overstory and understory trees on all 0.04-ha plots were sampled in 2005 (prior to thinning) and again at 5 and 10 years after thinning. Overstory trees are those in the B-stratum (upper continuous canopy) and include dominant, codominant, intermediate, and overtopped crown classes (Smith et al. 1997). Understory trees are those stems that are at least 2.54 cm d.b.h. with crowns located at least 2 m below the overstory. Canopy class and species were determined on all plot trees in addition to measurements of height class (3 m increments up to >15.24 m) and d.b.h. In 2005, all overstory trees were visually classified according to crown class. Measurements collected on the subject trees included: d.b.h., total height and height to base of live crown (using a clinometer), and crown width. Base of live crown was measured at the height above ground of the lowest cluster of branches (Kenefic and Seymour 1999). Crown width was estimated by measuring the length of the longest branch in four cardinal directions. Observers visually stood under the longest branch and used a Leica DISTOTM to shoot a laser back to the stem and record the distance. In 2005, observers placed permanent stakes at each measurement point to guide future remeasurements.

Analyses

Due to hemlock's irregular crown shape (Kenefic and Seymour 1999), CRAREA on each subject tree was estimated using a slight modification of an ellipse equation:

$$\text{Area} = \pi (ab)$$

where

a represents the average of the two longest radii, and

b represents the average of the two shortest radii.

LCR is calculated as: (total height – height to base of live crown) / total height.

The experiment is set up as a generalized random block design (Kirk 2012) with a repeated measures factor. Each of the four stands is considered a fixed variable because their location was not randomly determined. The six 0.4-ha treatment blocks within each stand are considered random variables because their treatment status was randomly assigned. The repeated measures factor is the plot remeasurements (time) on the thinned and unthinned treatments. Response variables tested on the subject trees were d.b.h., LCR, and CRAREA.

All analyses were conducted using the linear mixed models procedure (SAS 2018), and covariance structures were modeled using the REPEATED statement in the PROC MIXED procedure, with a maximum likelihood estimation set at alpha=0.05. Even though the data are temporal, with only three measurement periods the simplest correlation model of compound symmetry provided the best fit to the data. The model assumption is that correlation is constant regardless of the time between points. Post-hoc tests on least squares means were conducted as pairwise comparisons, and all *P* values were adjusted using the Tukey option.

RESULTS

Tests of the fixed effects indicated that all response variables had significant temporal, location (stand), and treatment effects (Table 1). The interaction of stand × time was not significant for either d.b.h. and LCR, and treatment × time was not significant for d.b.h. The lack of significance suggested that the slopes were not significantly different from each other across stands for both variables, and between treatments for d.b.h. Hence both interaction terms were dropped from the d.b.h. model and stand × time was dropped from the LCR model (Table 2).

Comparisons of least squares means of the new models (Table 2) indicated that even though d.b.h. showed overall significant stand and time effects, there were no temporal differences among stands or treatments. Both control and thinned stands increased in diameter over time and for all stands (Table 3). Comparisons of the least squares means showed d.b.h. among control blocks was significantly lower in Stand 2 compared to Stand 1 (*P*-value 0.0008) and higher in Stand 2 compared to Stand 4 (*P*-value 0.0001). Among thinned block comparisons, Stand 4 d.b.h. was significantly lower than both Stand 1 (*P* value 0.0002) and Stand 2 (*P*-value 0.0001).

LCR had a significant stand × treatment effect (Table 2) and all stands had significantly higher LCR in thinned stands (*P*-value <0.0001). LCR also had a significant treatment × time effect (Table 2) but comparisons of least squares means showed no significant differences among thinned blocks between years 1 and 5, 5 and 10, and 1 and 10. For control blocks, LCR significantly decreased between years 1 and 10 (*P* value <0.0001) and years 5 and 10 (*P* value < 0.0001) and was unchanged between years 1 and 5 (Table 3).

Table 1.— Linear mixed model Type 3 tests of the fixed effects variables: Diameter (d.b.h), LCR (live crown ratio), and CRAREA (crown area)

Effect	DF	Pr >F	Pr >F	Pr >F
		DBH	LCR	CRAREA
Stand	3	0.0131	<0.0001	<0.0001
Treatment	1	<0.0001	<0.0001	0.0303
Stand×Treatment	3	<0.0001	0.0002	<0.0001
Time	2	<0.0001	<0.0001	<0.0001
Stand×Time	6	0.9927	0.9339	0.0089
Treatment×Time	2	0.2978	<0.0001	0.0003

Table 2.— Linear mixed model Type 3 tests of the fixed effects variables diameter (d.b.h) and LCR (live crown ratio) after interaction terms Stand × Time and Treatment × Time (just for diameter) were removed from original models

Effect	DF	Pr >F	Pr >F
		d.b.h.	LCR
Stand	3	0.0070	<0.0001
Treatment	1	<0.0001	<0.0001
Stand×Treatment	3	<0.0001	0.0002
Time	2	<0.0001	<0.0001
Stand×Time	6	n/a	n/a
Treatment×Time	2	n/a	<0.0001

Table 3.—Temporal and treatment characteristics of 246 hemlock trees sampled from Time 1 (prethinning in 2005) and Times 5 and 10 years after thinning in 2007. Data presented are least squares means (+standard errors).

	Treatment					
	Control			Thinned		
Time	1	5	10	1	5	10
d.b.h. (cm)	27.9 (0.79)	30.0 (0.79)	31.2 (0.81)	32.8 (0.76)	35.6 (0.76)	38.4 (0.76)
Live crown ratio	0.67 (0.01)	0.65 (0.01)	0.59 (0.01)	0.68 (0.01)	0.67 (0.01)	0.68 (0.01)
Crown area (m ²)	44.1 (1.8)	41.4 (1.8)	51.6 (1.9)	41.6 (1.7)	42.2 (1.7)	62.8 (1.7)

CRAREA also had a significant overall stand × treatment effect with only Stand 4 showing no difference. There were also no significant differences between years 1 and 5 for either treatment but CRAREA increased for both treatments between years 5 and 10 (P values <0.0001) and 1 and 10 (control P-value 0.0035 and thinned <0.0001), although, the degree of increase over 10 years was greater in thinned blocks (Table 3).

DISCUSSION

Even though the original intent of this study was to test a preemptive HWA management strategy, we did learn that our thinning treatments produced the desired results, which could serve to mitigate HWA survival in the future. Currently, chemical HWA controls are not economically feasible at a forested landscape scale and biological controls have limited effectiveness (Mayfield et al. 2015, Vose et al. 2013). An integrated management approach combining chemical, biological, and canopy release has been tested at small experimental scales (Brantley et al. 2017, Ford Miniati et al. 2020) and suggests that increased canopy light exposure creates less favorable environments for HWA.

Our harvests were conducted at a commercial scale, yet we monitored both individual subject tree attributes, reported here, and also modeled stand-level growth (results in progress). Specific stand structural attributes guided tree-marking choices in achieving residual basal area goals. Stands were selected based on uniformity of hemlock distribution, basal area, and suitability for thinning according to stocking criteria. Each stand was unique regarding stand history so the differences among location and treatment were not unexpected. Subject tree growth increases due to thinning were anticipated but the rate of increase was questionable, especially because of the high initial density of Stands 1, 2, 3 (Compartment 301) with only one-third basal area removed. Yet, these three overstocked stands demonstrated improved crown attributes in directly released subject tree crowns. Hence meeting the objectives of the study.

There was no significant treatment $\times$ time interaction for d.b.h. because diameter increased in both thinned and unthinned stands over 10 years even though subject trees in thinned blocks increased an average of 6.1 ($\pm$ 1.8) cm while control trees increased 3.3 ($\pm$ 1.3) cm. The slower trend in control trees is representative of hemlock's high shade tolerance and steady growth even at high densities. Hemlock diameter responds slowly to partial canopy disturbances, especially after growth suppression, resulting in stands with highly variable individual tree growth rates (Fajvan and Seymour 1993).

Tree crown variables also responded positively to thinning. Eighty-seven percent of the unthinned trees averaged 18 percent LCR decreases and all trees in the thinned group increased an average of 7 percent. Subject trees in thinned blocks generally maintained their LCR over 10 years as control trees declined after year 5. Maintenance of LCR is one goal of thinning (Smith et al. 1997) and is especially important in reducing vulnerability to HWA (Rentch et al. 2009). All thinned trees showed some degree of CRAREA increase whereas only 8 percent of unthinned trees increased. Prior to treatment in 2005 most subject tree crown classifications were dominant/codominant: 90 percent in control and 77 percent in thinned. The rest were intermediate with only one overtopped (thinned). Stand 4 (Compartment 341), was the only stand that showed no treatment difference for CRAREA and as expected, it had significantly lower average diameters for all measurement periods. Initially this stand was structurally very different from the others with about half of the preharvest basal area and much smaller diameter hemlocks. Hence, most of the crown competition was in the mid-story hemlock clusters that were thinned. The overstory subject trees in that stand probably did not experience as dramatic a crown release as the other stands because the stand had much lower initial stocking.

When considering the entire stand, we attempted to maintain relatively uniform residual tree spacing in our marking efforts, therefore not all trees in thinned blocks had direct crown release. Yet, all residual trees benefitted due to stand density reductions and resulting site resource allocations. Ten years after thinning, our data indicate that relative stand density has increased enough to warrant a second thinning, or initiation of the shelterwood sequence, to sustain growth of released hemlock crowns. Maintenance of sufficient crown growing space will be a contributing factor in minimizing future impacts from HWA.

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Choice of Silvicultural System Influences Internal Wood Characteristics of Sugar Maple

Yvette L. Dickinson, Christel C. Kern, Robert J. Ross, and Xiping Wang¹

Quality is an important determinant of the end use of wood, and therefore its value. Silviculture and growing environment can influence wood characteristics of softwood species (Barnett and Jeronimidis 2003, Shmulsky and Jones 2011, Zobel and Van Buijtenen 1989); however, less is known about these influences in hardwoods (Dickinson et al. 2019). A number of tree species typical of northern hardwood forests such as sugar maple have been conventionally utilized primarily for aesthetic applications and are therefore graded visually. However, the recent expansion of engineered wood products has created new potential uses for hardwoods (Ross and Erickson 2005, 2020), and a greater understanding of wood quality is needed to allow continued development of these engineered wood products.

The objective of this study was to investigate the influence of silviculture on the fundamental physical and mechanical properties of sugar maple, a dominant northern hardwood species. We investigated the influence of silvicultural system on internal wood characteristics of sugar maple, primarily wood density, in a long-term silvicultural experiment utilizing nondestructive acoustic testing.

Transverse and longitudinal stress wave velocity at breast height, tree age, green moisture content, and oven-dry wood density were measured for 30 randomly selected live trees managed under each of seven silvicultural systems at the Dukes Experimental Forest (DEF), Hiawatha National Forest, Michigan (46.34236, -87.14078). Stress wave velocity is the speed which an acoustic wave takes to travel through a material and is known to have a strong relationship with a range of wood quality characteristics including wood density (Wang and Carter 2015). Furthermore, the stress wave velocity horizontally through the trunk of a tree in the transverse direction (across the wood grain), and vertically along the trunk in the longitudinal direction (along the wood grain) differ.

The study area is characterized by continental climate, although it is in close proximity (18 km) to a large body of water, Lake Superior. The average annual temperature is about 5 °C, the average snowfall about 355 cm, and the growing season length is 110 days. The soils are moderately to somewhat poorly drained sandy loams (Sheopac-Trenary and Reade silt loams) with site indices (at age 50) up to 20 m for sugar maple (NRCS 2007). The Partial Cuttings Study was established on the DEF in 1926 (Eyre and Zillgitt 1953). Prior to study establishment, the forest was in a late-successional stage of development and was dominated by large diameter sugar maple (*Acer saccharum* Marshall). Density of large trees >46 cm diameter at breast height (d.b.h.) was 64 trees/ha, while total stand basal area varied between 27 and 32 m²/ha. Minor species (<10 percent of tree density) were primarily yellow birch (*Betula alleghaniensis* Britton) with lesser amounts of American elm (*Ulmus americana* L.), eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Kock) and balsam fir (*Abies balsamea* (L.) Mill.).

While some of the experimental treatments included common practices of the time focusing on removing large trees (i.e., diameter-limit cutting), other treatments approaches tested were new

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to the forest type, such as improvement cuttings and selection systems. In the current study we revisited the 30 cm (12 inch) diameter limit, 55 cm (22 inch) diameter limit, 70 percent selection, clearcut, single-tree selection (originally called overmature and defective No. 1) and group selection treatments. Treatments were applied in stands (experimental units) 2 to 13 ha in size. Replication of treatments was uncommon in forestry research at the time and, consequently, the treatments were applied once ($N = 1$). The treatments were initiated between 1926 and 1932 and the most recent harvest occurred over winter 2008–2009. In addition, we utilized the nearby Dukes Research Natural Area (RNA) (<https://www.fs.usda.gov/research/nrs/rnas/usingrna>) as an old-growth, reference condition (control) to compare and contrast with the silvicultural treatments. This RNA is an area of uncut, old-growth forest and therefore trees within this area provide a good representation of the wood characteristics of trees grown without silvicultural treatments.

Transverse and longitudinal stress wave velocity were measured using the time-of-flight method. Two sensor probes (transmit probe and receiver probe) were inserted into the sapwood and acoustic energy introduced into the tree through a hammer impact on the transmit probe. The time taken for the stress wave to travel between the two probes was measured, and the speed of travel calculated. During this study, the probes were inserted into the tree trunk (through bark and cambium to extend into the sapwood) and aligned within a vertical plane on the same face. The lower probe was placed about 40 to 60 cm above the ground. The span between the probes were determined from a practical standpoint, typically in the range 1.0 to 1.2 m. In addition, acoustic wave velocity was measured in the transverse direction at d.b.h. The two probes were placed either side of the tree, and measurements recorded as above.

Green moisture content, oven-dry wood density, and tree age were measured using a pith-to-bark increment core collected at breast height. The core volume and weight were recorded in the field immediately after collection, and again after being oven dried at 100 °C to a consistent weight. The moisture content and wood density were then calculated. Each core was mounted and sanded, and tree rings counted under a microscope.

We used multiple linear regression to statistically test whether longitudinal and transverse stress wave, respectively, were predictive of oven-dry wood density. Moisture content is known to influence stress wave velocity; therefore, green moisture content of the increment core from each tree was included as a covariate. Furthermore, age was included as a covariate as it also potentially influences wood characteristics. All assumptions of multiple linear regression were examined and satisfied. Where the covariates were not significant ($\alpha = 0.05$), they were removed from the final analysis model. We also used ANOVA to statistically test whether longitudinal and transverse stress wave velocities, and wood density, respectively, vary among the six silvicultural treatments and control treatment. Similarly, moisture content and age were initially included as covariates, but removed where not significant. All assumptions of ANOVA were examined and satisfied. Where the ANOVA was significant, follow-up *ad hoc* Tukey tests were used to identify which of the treatments had statistically significantly different stress wave velocities. All analyses were undertaken using R version 4.0.3 (R Core Team 2019).

We found that transverse stress wave velocity is a statistically significant predictor of measured wood density ($P < 0.001$) suggesting that it may be used to indicate internal wood quality of standing sugar maple trees; however, this relationship is influenced by tree age ($P = 0.017$; Fig. 1). Oven dry wood density increases with increased transverse stress wave velocity and tree age. In contrast, longitudinal stress wave velocity is not a statistically significant predictor of measured wood density ($P = 0.977$) and cannot be used to indicate internal wood quality of live sugar maple.

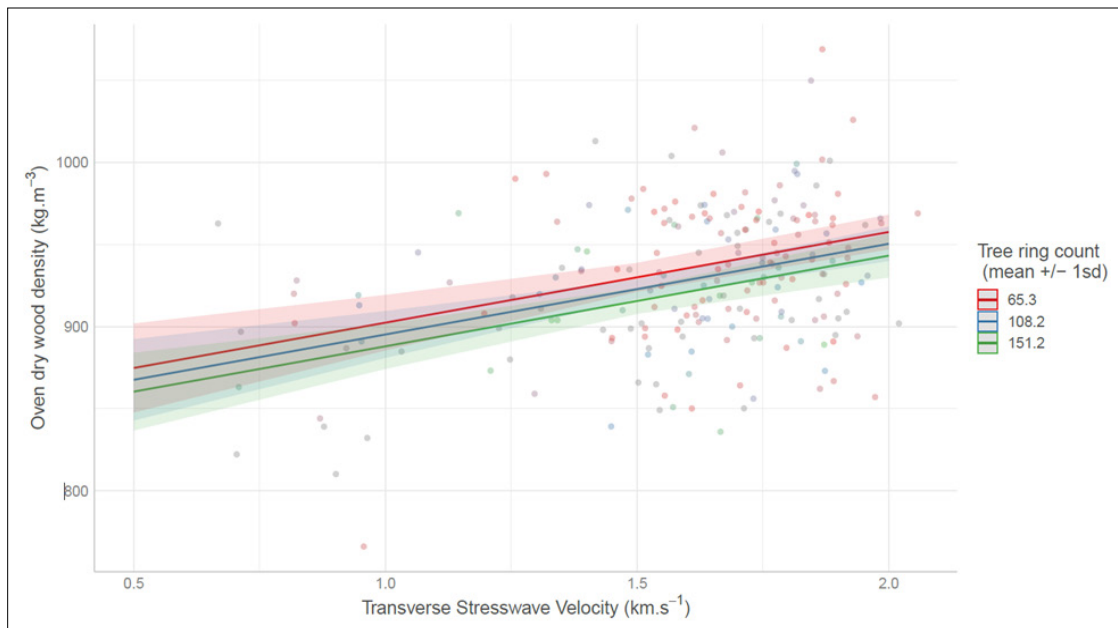


Figure 1.—Oven dry wood density increases with increased transverse stress wave velocity and tree age.

We also found that both transverse stress wave velocity and wood density of sugar maple varied significantly among the silvicultural systems, suggesting that the choice of silvicultural system influences internal wood characteristics of sugar maple.

Transverse stress wave velocity varied significantly among the silvicultural systems ($P < 0.001$; Fig. 2); however, tree age ($p = 0.003$), green moisture content ($P < 0.001$), and a silvicultural system $\times$ moisture content interaction term ($P = 0.002$) were all statistically significant covariates. Trees in the old-growth control had significantly slower velocities than overmature and defective No. 1; 12-inch diameter limit; and 22-inch diameter limit silvicultural systems ($P < 0.001$, $P < 0.001$, and $P = 0.015$, respectively).

In addition, wood density varied significantly among the silvicultural systems ($P < 0.001$), irrespective of tree age ($P = 0.314$). Trees in the old-growth control had statistically significant lower wood density than the 12-inch diameter limit, overmature and defective No. 1, 70 percent selection, and clearcut ($P = 0.025$, 0.012 , 0.009 , and 0.005 , respectively; Fig. 3). The increased wood density under these silvicultural systems compared to the control indicates that they are likely to have improved wood quality characteristics.

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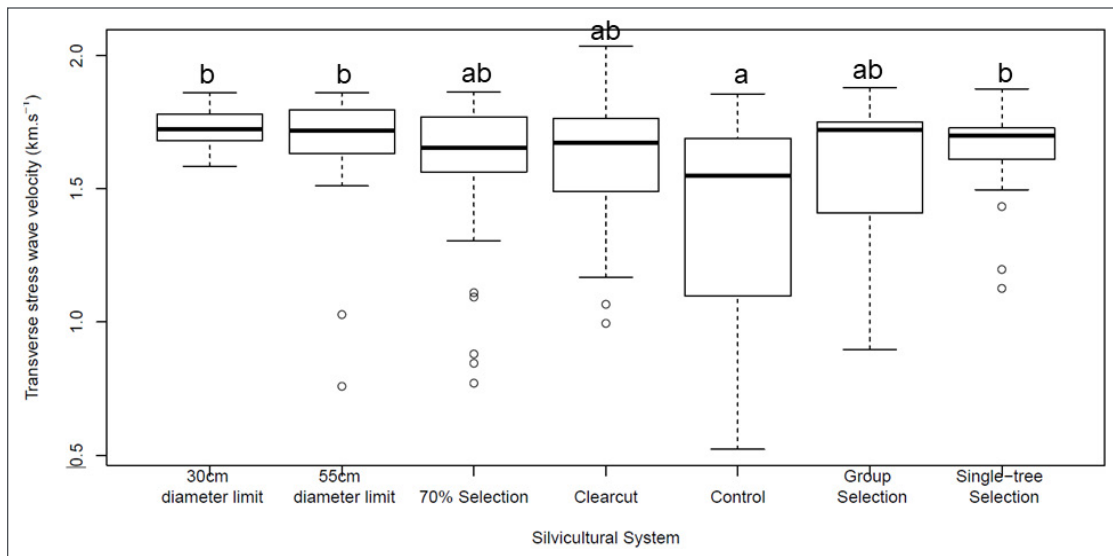


Figure 2. —Transverse stress wave velocity varies significantly among silvicultural systems. Letters indicate statistically significant differences.

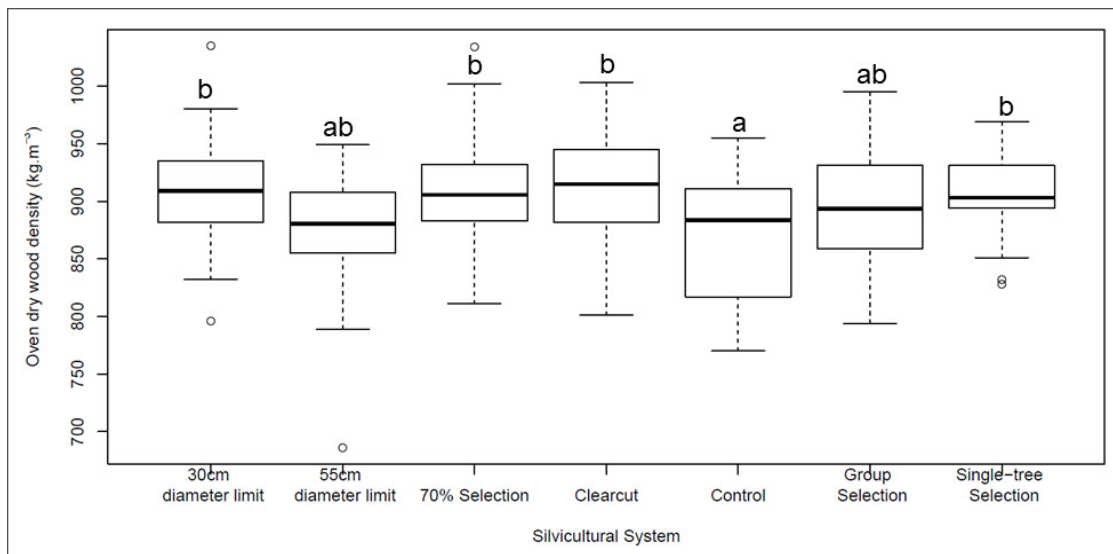


Figure 3. —Oven dry wood density varies significantly among silvicultural systems. Letters indicate statistically significant differences.

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FOREST PRODUCTS AND ECONOMICS

The Northern Hardwood Resource: A Market Perspective

William G. Luppold and Matthew S. Bumgardner¹

The hardwood resource of the eastern United States often is associated with high quality sawtimber used in the production of lumber and veneer consumed in domestic appearance applications or exported. However, the high quality segment of the eastern hardwood resource accounts for approximately 20 percent of the cubic volume of merchantable trees (Luppold and Pugh 2016). In the northern regions of the eastern United States, the proportional volume of higher quality timber is discernably larger. Still, combined mid- and low-quality sawtimber size (11 inches d.b.h. and larger) tree volume exceeds the volume of high quality timber in the Northeast and Lake States regions and the quality characteristics of this resource are changing (Table 1).

Since 2009, 65 percent of the increase in volume in sawtimber-size trees in the Northeast has been in the low quality category (Table 1). Northeast hardwood poletimber (5 inches $\leq$ d.b.h. $\leq$ 10.9 inches) volume also has declined (USDA Forest Service 2021). At the turn of the century, 37 percent of the Northeast merchantable timber was in the poletimber size class. By 2019, poletimber volume had decreased by 3 billion cubic feet from turn of the century levels and accounted for 29 percent of the merchantable timber volume. The quality of this poletimber also is decreasing, as cull volume of this tree-size has increased while growing stock poletimber volume has decreased (Luppold and Bumgardner 2019). The changes in poletimber volume could be indicative of an aging resource. One potential cause of the increase in low quality sawtimber-size tree volume is age-related degrade prior to mortality.

A large portion of the increase in Lake State hardwood sawtimber tree volume between 2009 and 2019 was in the mid-quality category (Table 1). This category includes smaller diameter but well formed trees as well as mid-quality trees of all diameter classes. The increase in mid-quality tree volume in the Lake States was, in part, the result of poletimber transitioning to sawtimber-size trees (USDA Forest Service 2021). While poletimber volume also is declining in the Lake States,

Table 1.—Volume of sawtimber-size hardwood trees in the Northeast and Lake States (developed using procedures presented in Luppold and Bumgardner 2019 for regions developed in Luppold and Bumgardner 2021a using data from USDA Forest Service 2021)

Tree quality	Northeast ^a		Lake States ^b	
	2009	2019	2009	2019
---million cubic feet---				
High quality – tree grades 1 and 2	24,142	25,472	9,053	10,731
Mid quality – tree grade 3	20,405	21,898	9,832	11,676
Low quality – below tree grade 3 (and incl. cull)	16,222	21,469	10,212	11,166

^a Includes the states of PA, NJ, NY, CN, RI, MA, VT, NH, and ME

^b Includes the states of MI, WI, and MN

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it still accounted for 38 percent of the timber base in 2019 and poletimber decline has not occurred across all species groups. Two important species groups for which poletimber volume increased between 2009 and 2019 are soft maple (*Acer* spp.) and cottonwood and aspen (*Populus* spp.).

Another factor that will affect long-term timber supply is mortality (Luppold and Bumgardner 2021a). Increased mortality in the Northeast and Lake States is most evident in ash (*Fraxinus* spp.), a result of the emerald ash borer (*Agrilus planipennis*). However, mortality has been increasing in both the Northeast and Lake States as greater portions of the standing timber becomes mature. By contrast, hardwood sawtimber removals declined in all regions except the Lake States and Central regions. With the exception of ash, there were no indications of immediate declines in eastern sawtimber volume as a result of mortality. However, continual increases in mortality, a resurgence of removals, and reduced growth could cause sawtimber volume to plateau in the coming decades.

While changing timber quality is an issue that economists must examine when evaluating the long-term potential of the northern hardwood timber base, perhaps a more important issue currently affecting timber investment and management decisions is the decades long decline in hardwood lumber prices (Luppold and Bumgardner 2021b). After trending upward between 1980 and 2000, real (inflation-adjusted) hardwood lumber prices have trended downward this century. This decline is the result of declining domestic demand for lumber used in appearance applications including furniture, kitchen cabinets, flooring, and millwork (Luppold and Bumgardner 2016).

Hardwood lumber used in domestic appearance applications reached its highest level in the late 1990s (Luppold and Bumgardner 2016). The combined markets for appearance lumber and exports peaked at 7.25 billion board feet in 2000 (Luppold and Bumgardner 2021a). Declines in furniture production after 2000 in combination with the decline in home construction after 2006, followed by the Great Recession (December 2007 to June 2009), caused appearance lumber consumption plus exports to fall to less than 3.3 billion board feet in 2009. Since 2009, exports have become an extremely important market for higher quality hardwood lumber. By contrast, hardwood lumber consumption in the furniture industry, especially the wood and upholstered household furniture portions of this industry, has continued to decline.

The decline in lumber use by the furniture industry has been influenced by a decline in domestic furniture production (Luppold and Bumgardner 2022). Between 2000 and 2009, the wood consuming furniture manufacturers (WCFM, which includes wood household, upholstered household, and wood office and related products) experienced a 51 percent decline in the real value of domestic shipments. This decline was associated with a 75 percent decline in hardwood lumber use in furniture manufacturing during this period (Luppold and Bumgardner 2016). The larger decline in lumber consumption versus the decline in the value of WCFM shipments was the result of reduced use of hardwood lumber per unit value of furniture produced.

After 2009, WCFM shipments fluctuated but still were 48 percent below 2000 levels in 2019 (Luppold and Bumgardner 2022). A major contributor to the decline in the value of domestic household furniture shipments since 1997 has been furniture imports. In 1997, imports accounted for 6 and 23 percent of the upholstered household (UHF) and wood household furniture (WHF), respectively, available to U.S. consumers. In 2019, imports accounted for 35 and 78 percent of UHF and WHF, respectively, of these same markets.

Another factor influencing WCFM shipments is domestic consumption. Between 1997 and 2019, domestic consumption of UHF increased but since 2002 this increase has been satisfied through increased imports (Luppold and Bumgardner 2022) Since 2005, domestic consumption of WHF

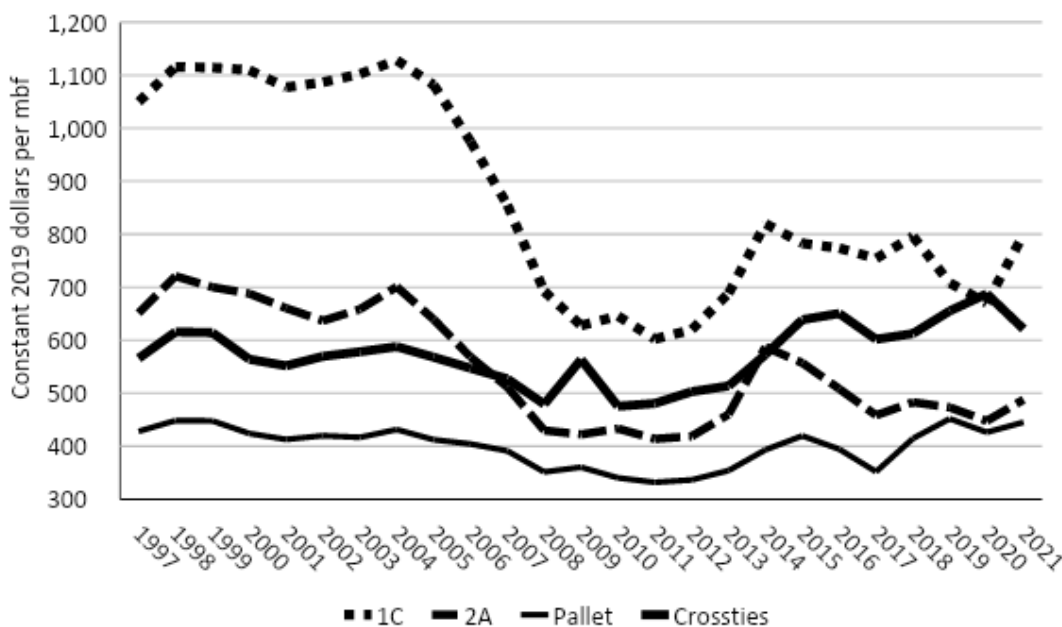


Figure 1.—Resource-weighted (aggregate) 1C and 2A lumber prices compared to pallet cants and crosstie prices in the Northeast U.S. region, 1997 to 2021.

declined by 45 percent. Consumptions of wood office furniture and related products declined by 40 percent between 2000 and 2019 but imports of these products have remained at a relatively low level since 1997.

The declines in lumber prices that resulted from reduced domestic demand in appearance applications have not been uniform across regions and species (Luppold and Bumgardner 2021b). The greatest declines in lumber price occurred in the Northeast and Lake States regions (with smaller declines occurring in the Central, Southern, and mid-Atlantic regions). With the exceptions of white oak (*Quercus* spp.) and walnut (*Juglans nigra*), prices of high value species have declined more than prices of low value species.

While hardwood lumber prices have declined, prices for pallet cants have remained relatively constant since 1997 and the price of crossties has trended upward (Fig. 1). In 2020, the price of pallet cants approached the aggregated price of grade 2A hardwood lumber in the Northeast and crosstie prices exceeded that of aggregate 1C lumber (Luppold and Bumgardner 2021b).

The hardwood industry adapts constantly to changes in market demand and utilizes the available timber resource in providing products in response to these demands. Still, there have been discernable longer term market trends. Hardwood timber managers must concurrently recognize these market trends and changes in the hardwood timber resource to maintain long term forest health and viability.

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Hardwood Markets in 2020 and Beyond

Brian K. Brashaw, Troy Brown, Judd Johnson, Robert J. Ross, and Charles Becker¹

Abstract.—United States hardwood production and markets have seen a number of ups and downs over the last 20 years since peak production in the late 1990s, followed by historic lows during the “Great Recession” in 2009 and a slowly recovering industry since. During this time, we have seen the loss of domestic furniture and cabinet markets, increases in forest product export markets, trade disputes, reduced grade-lumber, and increased industrial wood demand, and most recently the COVID-19 crisis. With this backdrop, presenters from forest industry, wood market pricing services, and wood products research discuss present and future outlook for hardwood markets.

FOREST INDUSTRY MARKET PERSPECTIVES

Hardwood Market Overview and Commentary

The U.S. hardwood industry has experienced an era of change that forced contraction in lumber production and processing capabilities. Much of that change can be attributed to specific events that disrupted downstream markets, raw material flows, and labor. Yet, there are other forces less epic in nature that have continually eroded market share for hardwoods over time. From an annual peak of 12.6 billion board feet (BBF) in 1999, eastern U.S. hardwood sawmill production dropped to 10.8 BBF per year by 2006 (-14.4 percent). Notably, 2006 was still in the period of historically high residential construction in the United States. By the end of the Great Recession in 2009, eastern U.S. hardwood sawmill production fell to its then lowest level on record at 5.7 BBF per year.

Economic expansion and increased consumerism in China helped lift U.S. hardwood sawmill production and shake off poor markets of the post-Great Recession. However, overreliance on that one market made the U.S. hardwood supply grid vulnerable. The U.S./China trade war and slowing Chinese economy starting in 2018 pushed back demand for high valued grades of key U.S. hardwood species. The impact on sawmill output from the China market downturn was comparatively minimal. However, the monetary effects on U.S. hardwood sawmills from contracted Chinese business were substantial.

Importantly, the U.S. hardwood supply grid was in a weakened financial state prior to the coronavirus pandemic. Therefore, the effects on U.S. hardwood sawmill production during the peak of business closures from April through June 2020 were more severe and lasting than they might have been otherwise.

Eastern U.S. hardwood sawmill production ended 2020 at 5.6 BBF or 25.6 percent below 2019 level—a new record low. For the first time in Hardwood Market Report’s sawmill production data series, the annual rate of monthly output dropped below 5 BBF and held below that threshold

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for five consecutive months. May 2020 recorded the lowest annual rate of eastern U.S. hardwood sawmill production at 4.3 BBF.

The COVID-19 pandemic created an extraordinary set of events. Hardwood Market Report estimates total *demand* for U.S. hardwood lumber to be in the 8 BBF range, therefore, an obvious supply gap exists. However, the projected market demand has greatly diminished over time. Moreover, the market makeup that influences sales values is inverted, shifting from a 60:40 percent ratio of higher valued grade lumber to lower valued industrial lumber to what is now a 40:60 percent mix. Consequently, there is less total revenue being generated by the hardwood industry, and margins are squeezed.

Intervals of severe business disruptions have depleted wealth from the U.S. hardwood supply grid. Market recovery periods help restore some of the losses. But these rebounds inherently fuel raw material price inflation that reduce margins as the recovery period advances. Also, it is the higher costs of material accumulated during the recovery process that almost always set sawmills up for future losses when business momentum subsides.

The business downturns have become more frequent starting with the Great Recession, and the ability for sawmills to recover from lost business and revenue is weakened. Sawmill owners and managers see greater financial risk and less financial reward as they resume normal operations. At the very least, they are hesitant to commit additional resources for increasing production capacity utilization. They are far more cautious when considering expanding production capacity.

U.S. hardwood companies have been set back. But despite challenges and risks, opportunities exist for better business. It is now, after many years, that the industry is structuring an organized means to cultivate market opportunities and develop new ones. The Real American Hardwood Promotion (RAHP) was officially rolled out in June 2021. Like any new venture, its success is uncertain. On the other hand, the results from doing nothing are quite clear.

Hardwood Producer

Hardwood lumber producers report that the current high pricing in the hardwood industry is based on high demand and production (supply) that is down. The volatile conditions over the past years have impacted current production through mill closings and stagnant production in mills that survived. Specific reasons included that some mills have closed or are still recovering from previous economic downturns, unwillingness to reinvest in mill or increase production, loss of logging capacity, finding employees, and concerns about the future.

To address current demands, mills need to find ways to attract more employees, increase communication with customers, and to develop alternative solutions through species or grade substitution. Lack of timber resources is not the issue. Logs are available through programs like the Good Neighbor Authority, active forest management by private landowners, forest health, and storm damage recovery.

Several conditions are predicted to affect future hardwood lumber availability and price. These include higher interest rates, government tension, housing starts, remodeling declines, and increasing mill production. To prepare for the future, the Real American Hardwood Coalition (RAHC) was formed in 2019 and currently includes 28 trade associations and industry partners. RAHC conducted research on consumers' views of hardwood. The research showed that customers consider hardwood attractive, with high-end appeal, unique, durable, and the "gold standard." However, drawbacks to hardwood identified include cost and that it is not considered a good value. In a disposable society, the appeal of real American hardwood is undermined by "close

is good enough.” Planned steps for the RAHC hardwood promotion project are to establish a strong digital presence, partner with social media influencers, and develop promotional materials and relationships with large and small retailers. Part of the promotion will be to familiarize consumer markets in the northern hardwood region about various visual grades of lumber including first and seconds (FAS) lumber for millwork and west coast distribution; one common (1C) lumber for domestic cabinet and furniture overseas; two common (2C) lumber for cabinets and flooring; 3A lumber for flooring, pallets, and ties; and 3B lumber for pallets and ties.

Structural Hardwood Research

The USDA Forest Service has been actively involved in research and market development for structural uses of hardwood. The presentation summarizes information on the use of wood from hardwood species in engineered materials, components, and structures. It includes information on use in a wide variety of engineering products and applications including glued-laminated timbers, laminated veneer lumber, trusses, cross-laminated timber (CLT), working tool handles, laminated propellers for military drones, and sporting goods. New opportunities are available for hardwood lumber but will require innovative partnering to bring to market. A comprehensive report, “Undervalued Hardwoods for Engineered Materials and Components” (Ross and Erickson 2020) is available through the Forest Service.

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Overview of Wisconsin's Value-Added Wood Manufacturing Industry

Scott W. Lyon¹

Abstract.—The valued-added wood manufacturing industry includes firms that use primary wood products, such as lumber or veneer, to produce higher value products, including flooring, cabinets, or furniture. Wisconsin's value-added wood industry is an important sector for the State's economy and serves as a vital downstream market for forest raw materials. A survey was conducted with the Wisconsin value-added wood industry in 2018 to better understand the current economic impacts, markets, and needs of this industry. Results suggest that employment opportunities exist. Enrollment in a forest certification and/or chain-of-custody certification program was uncommon among respondents. This study found there is an opportunity to substitute locally grown commercial species instead of using out-of-the-region species such as southern yellow pine and alder. Lastly, results indicated additional need for educational training to support the value-added wood industry, particularly in the areas of manufacturing and processing.

INTRODUCTION

Wisconsin's valued-added wood industry is an important sector for the State's economy and serves as a vital downstream market for forest raw materials. The industry includes more than 800 establishments, employs more than 20,000 workers, and generates a direct economic impact \$3 billion (WI DWD 2019, IMPLAN 2017).

During the last two decades, the U.S. forest products industry has experienced challenges. Similarly, to other domestic markets, wood manufacturers have lost market shares to low-cost producers overseas. In the 2000s, many value-added firms closed operations in the United States or moved production facilities overseas where reduced labor costs, reduced regulations, and lower energy costs allowed for cheaper production. Domestic consumption of hardwood lumber shifted from being used in manufacturing of furniture to producing industrial wood products, such as railroad ties and crane mats. Also, the decrease in domestic housing starts during the 2007–2009 recession led to a decline in consumption of wood products in construction and remodeling (Buehlmann et al. 2017, McKeever and Elling 2015). In residential construction, wood products are used as building materials (roof trusses and beams, framing, windows and doors) and appearance wood products (trim, flooring, and cabinets). Additionally, substitute materials such as steel and plastics have created market competition for wood products. Many of these substitute products are being used in flooring, furniture, millwork, and cabinets. However, wood has many benefits. Wood is a renewable resource as opposed to substitute nonrenewable products such as concrete, steel, and plastics. Less energy is required when manufacturing with wood than steel. Also, wood has been shown to increase human health and wellness when used in visual applications such as furniture, flooring, ceilings, and walls (Nyrud and Bringslimark 2010).

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Table 1.—Wood products manufacturing type by respondent (n=201) (companies could choose multiple responses)

Wood Product	Respondents	Percentage of Total
Millwork	106	52.70%
Architectural woodwork	62	30.80%
Furniture	55	27.40%
Hardwood and softwood lumber	47	23.40%
Hardwood dimension components	41	20.40%
Laminated counters & laminated other	28	13.90%
Containers, crates, pallets or skids, pallet parts	27	13.40%
Roof trusses, beams, particleboard, plywood & panels	25	12.40%
Crafts, models, toys, picture frames, & sporting goods	19	9.50%
Firewood, fuel logs & pellets	14	7.00%
Patterns	14	7.00%
Blocking	11	5.50%
Fencing	7	3.50%
Partitions & fixtures	7	3.50%
Veneer	7	3.50%
Boats and ships	2	1.00%
Caskets	2	1.00%
Lathe and stakes	1	0.05%

METHODS

From July to September 2018, an online and mail survey was conducted with Wisconsin's value-added wood-using industry. Mail and email lists were compiled by using both past editions of the Wisconsin Wood Using Industry Directory and known wood products manufacturer locations that were not listed in the directory. The goals of the survey were: (1) to update contact information in the Wisconsin Wood Using Industry Directory in order to serve local markets and forest utilization, (2) determine the impact of the secondary wood industry on Wisconsin's economy and (3) develop an understanding of educational and training needs of Wisconsin's secondary wood manufacturers. The survey was sent to 507 businesses across Wisconsin, using the Dillman's Tailored Design Method (Dillman 2000). The mailings consisted of a cover letter and questionnaire, a reminder letter, a second copy of the questionnaire, and a final reminder letter. Question topics included: demographics, wood product production, wood product purchasing, forest certification program enrollment, and educational training needs. In total, 205 completed surveys were returned. After eliminating undeliverable addresses and closed businesses from those contacted, the adjusted response rate for the survey was 51 percent.

RESULTS

Manufacturer Demographics and Types of Products Produced

Manufacturer demographics consisted of 163 firms with a single facility and 27 with multiple facilities that responded to the survey. Sixty-six percent of responding companies had fewer than 25 full time employees and produced less than \$5 million annually. Companies ranging from 25 to 99 employees (22 percent) reported sales from \$1 million to \$50 million. Only 12 percent of respondents had more than 100 employees. Most respondents identified as millwork manufacturers (n = 106 firms), architectural woodwork manufacturers (62), and furniture (55) (Table 1). Some of the respondents indicated that their companies were identified as more than one manufacturer type.

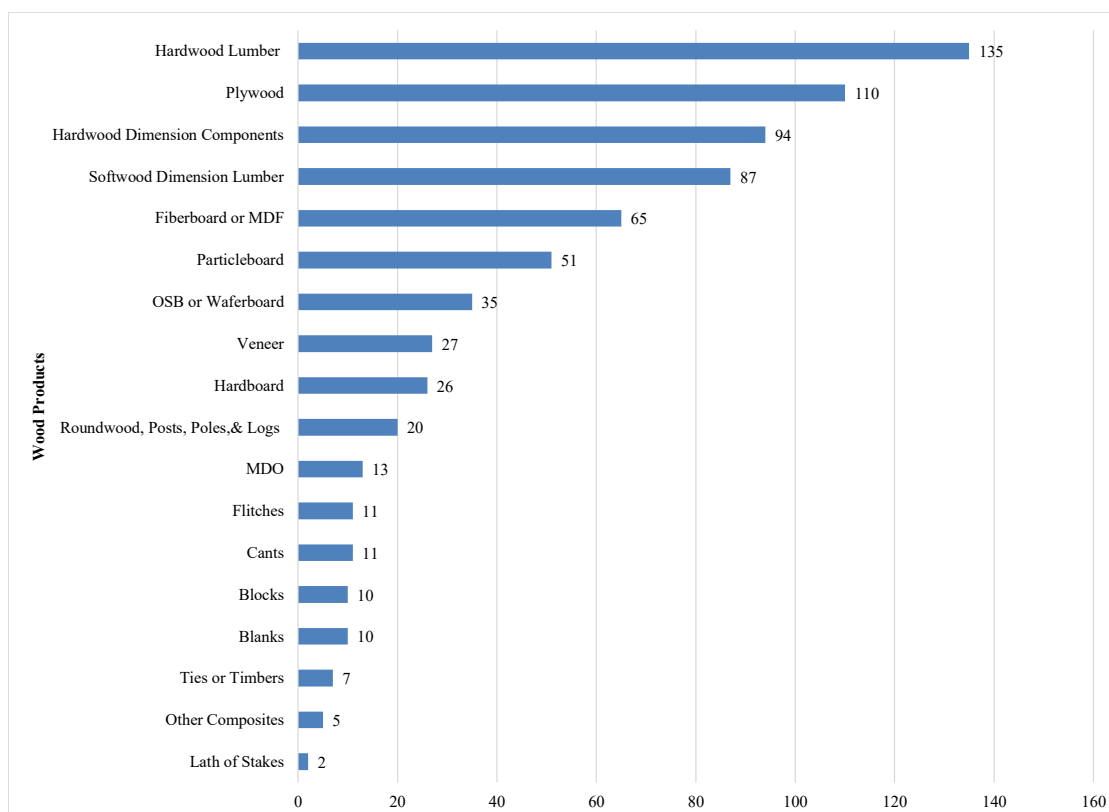


Figure 1.— Wood products purchased by responding companies (n=180); companies could choose multiple responses.

Types of Wood Products and Lumber Species Purchased

The most purchased wood products were hardwood lumber, plywood, hardwood dimension components, softwood dimension lumber, and fiberboard or medium density fiberboard. Other products purchased by respondents included: sawdust, wood shavings, urban wood (Fig. 1).

Of the companies that purchased lumber, the top hardwood species purchased were red oak, hard maple, cherry, white oak, and soft maple. These hardwood species were primarily used in cabinets, millwork, furniture, flooring, containers, and pallet manufacturing. The main softwood species used in manufacturing were eastern white pine (*Pinus strobus*), Douglas fir (*Pseudotsuga menziesii*), western red cedar (*Thuja plicata*), southern yellow pine (*P. echinata*), and red pine (*P. resinosa*). Companies purchasing eastern white pine included: millwork manufacturers and furniture makers. Other softwood species were used in manufacturing of roof trusses, laminated beams, containers, pallets, and fencing.

Extent Enrolled in Forest Certification

Only 19 percent of firms indicated that they were currently enrolled in either a forest certification program or a chain-of-custody certification program. Where multiple responses were possible, more manufacturers were certified by Forest Stewardship Council than the Sustainable Forestry Initiative (15 percent vs. 4 percent, respectively).

Educational Training Requirements and Frequency of Labor Shortages

Manufacturers rated the importance of 11 training categories using: not at all important, not too important, unsure, fairly important, and very important. Training in workplace safety, lean manufacturing, process improvement, and marketing/sales were rated relatively high on the importance scale among the respondents.

Thirty-six percent of companies reported that they often or always experience a labor shortage. Smaller companies tended to report less turnover of employees compared to larger manufacturers. Companies with 25 or more employees had a shortage of employees often or always.

SUMMARY

Wisconsin's value-added wood manufacturers produce a diverse array of products ranging from furniture and millwork to industrial products, such as crates and pallets. The results showed that employment opportunities exist across the industry with most of responding companies experiencing some sort of labor shortage, especially larger companies. Enrollment in forest certification or chain-of-custody certification programs was the minority among respondents. Of those that were certified, firms who responded to the survey were more likely to be enrolled in the Forest Stewardship Council program compared to other programs.

Most of the respondents purchased and sold wood products domestically. Global markets for valued-added wood products from the United States are minimal because of low labor and production costs overseas. There may be an opportunity to substitute locally grown commercial species such as red maple (*Acer saccharum*) and red or white pine for wood species that are being purchased outside of Wisconsin, such as red alder, southern yellow pine, and ponderosa pine (*P. ponderosa*). This study indicated a continued need for educational training for the value-added wood industry, particularly in the areas of manufacturing and processing.

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Timeless and Thoroughly Modern: Maple Syrup Production in the Twenty-first Century

Mark Isselhardt¹

BACKGROUND

The collection of sap from dormant maple trees in eastern North America predates European arrival on the continent. While written accounts of maple production by Native Americans from early French explorers exist from the late 17th century, a far richer oral history of how early cultures came to produce a sweet product from maple trees is best told by members of those cultures themselves.

Fundamentally, maple sap and maple syrup are nontimber forest products (NTFP). This fact immediately creates both challenges and opportunities for communication and engagement with stakeholders as well as adoption of specific management strategies as compared to traditional northern hardwoods forestry. The techniques used to harvest sap for a large extent of the history of maple production were dependent on a certain pattern of weather during the spring harvest season. Modern methods and equipment have allowed for sap to be collected during times when historical methods would not.

While the technology used to harvest maple sap has evolved over time, several fundamentals remain unchanged. The process still requires drilling holes to expose conductive xylem tissue of dormant trees. Although the maple industry standard for tap hole diameter has decreased by nearly 30 percent over the past 30 years (from 7/16 inch to 5/16 inch) the trees' wound response mechanism to tapping injury remains unchanged (Heiligmann et al. 2006). The active process of compartmentalization with the trees results in annual accrual of a volume of nonconductive wood (Walters Shigo 1978). New annual growth adds conductive wood. Recent research shows that tree size is strongly and linearly related to syrup yield (Isselhardt et al. 2018).

For more than 150 years, maple sap was harvested most commonly as a component of other agricultural production on small farms across the eastern United States and Canada. According to USDA statistics in 1909, there were 87,537 U.S. farms reporting maple production with an average of 216 taps/farm (USDA NASS 2021). The transition away from broadly distributed agricultural production in the early 20th century was swift and was reflected in the significant decline in production of maple sugar and syrup. Between 1909 and 1940, U.S. maple production declined by nearly 98 percent (Fig. 1). What followed was a roughly 50-year period of production on those farms and forests that remained active. Starting in the mid to late 1990s, a period of expansion began to take place in the country. The rate of expansion increased significantly to a point where U.S. current production has grown by 3.5 times in just the last 20 years (USDA NASS 2021). The average size of U.S. maple operations has also increased. According to the most recent USDA Census of Agriculture, the average size of U.S. maple operations is 1,410 taps/farm (USDA NASS 2021).

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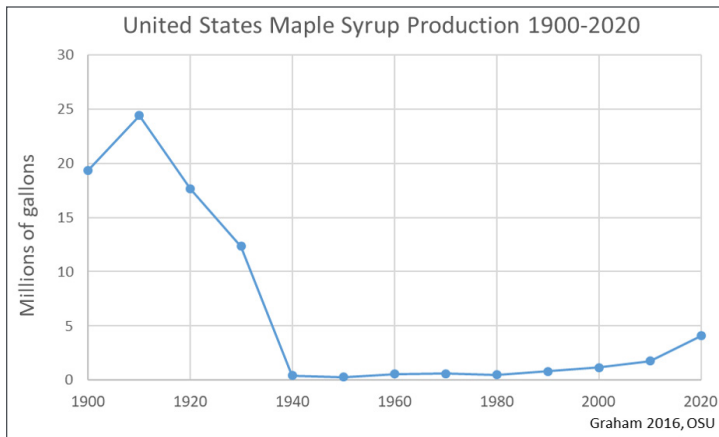


Figure 1.—Maple sugar producer in the United States, 1900 to 2020. Data from Graham 2016.

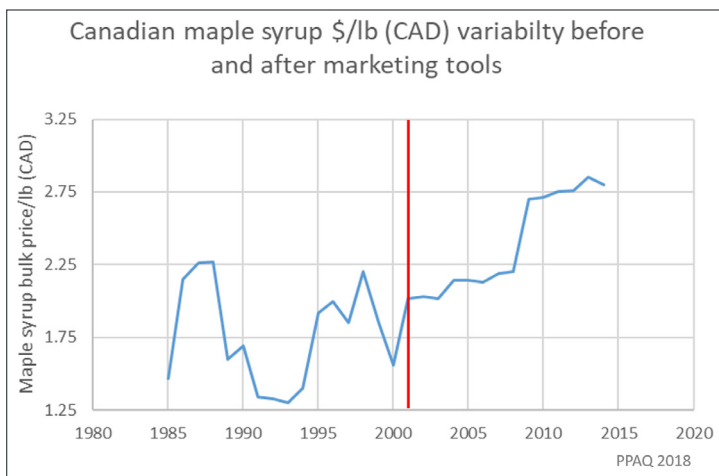


Figure 2.—Canadian maple sugar prices, 1985 to 2014, in Canadian dollars per pound of syrup.

CURRENT CONCERNS

Modern maple syrup production techniques involve the use of plastic tubing, vacuum pumps, and membranes to maximize sap yields, minimize labor costs, and reduce energy consumption in the processing of sap to syrup. Average sap yields have increased nearly 50 percent from ~0.2 gallons of syrup/tap 30+ years ago to >0.3 gallons of syrup/tap in 2020 (USDA NASS 2021). Research has shown that yields of 0.5 gallons of syrup/tap are achievable assuming modern technology, sanitation, and tree factors are followed (Isselhardt et al. 2018). Operation size is also an important factor as there are apparent economies of scale when adopting modern production technology. A recent survey of 312 maple producers from across the northeastern United States showed that approximately 81 percent of all reported syrup production came from producers with >5,000 taps although those operations translate to only 18 percent of all survey respondents (Cannella et al. 2021). There has been significant growth in the largest size operations over the recent past with a 9 percent increase in operations with >10,000 taps from 2002 to 2017 (USDA NASS 2021). Beyond the efficacy of large operations, the impact of Québec maple production and how that province's maple producers are organized helps explain the expansion of maple in the United States.

The Québec Maple Syrup Producers (QMSP) represents nearly 11,300 maple producers through a series of government sanctioned marketing tools including: provincial subsidies, favorable leases on publicly owned “crown land,” a quota system for controlling supply, and establishment of a strategic reserve of syrup. Following the implementation of the marketing tools and policies in the late 1990s and early 2000s the bulk price for pure maple syrup saw a reduction in volatility that was historically significant given the crop's reliance on ideal weather during the 6 to 8 week production season (Fig. 2; Hall 2013).

ECONOMICS

The financial returns for maple syrup production are variable. Net returns for a small group of producers in the Northeast who participated in a University of Vermont Extension Service financial benchmarking project averaged \$122/acre in 2019 with a range from -\$295 to \$605 (Cannella and Lindgren 2021). One factor that can contribute to the relative profitability of a given maple operation is access to crop trees. Many maple producers lease a portion or all their trees. Lease rates are variable and, in one report from Vermont, ranged from \$0.5 to >\$2.00/tap (Isselhardt 2017). The highest lease prices were paid for properties in areas with increased competition from other maple producers. Operations with excess sap processing capacity appear to be willing to pay more for leases.

Third party certification of organic maple syrup production has grown significantly in the United States. Although synthetic pesticides are rare in maple production, it is only until the operation has been inspected and shown to follow certification guidelines that the operation can market their product as certified organic. Standards vary among organizations but all require producers to follow a forest management plan that includes provisions for good forestry and maintaining species diversity. In 2008, the first-year records were compiled, 25 percent of the U.S. maple syrup crop was certified organic. In 2019, that number has more than doubled to 59 percent (USDA NASS 2021). The premium paid for certified organic syrup (~10 to 15 percent compared to “conventional” syrup) combined with the relatively low cost of obtaining certification helps explain recent trends.

Given the considerable time it takes for maple trees to become large enough to tap, the growth of maple production in the United States over the last 30 years has come from existing northern hardwood stands, many of which were at the time in active management for timber production. While the rate of growth in maple production has been dramatic, in terms of percent of trees capable of being tapped, the number remains relatively low. By some estimates only a few percent of the “tappable” trees in the nation are currently tapped. Vermont leads in terms of utilizing maple forests for sap production in the United States. Vermont maple producers tap roughly 12 percent of the 32 million potential taps in the state compared to Michigan that taps <1 percent of its 69.7 million potential taps (Matthews and Iverson 2017).

LOOKING FORWARD

Given consumer trends globally toward more natural, minimally produced foods and recent patterns of consumption, it appears that maple syrup is well positioned to benefit with increased demand. Gaps in the science as to the how modern sap collection methods and forest management activity can coexist remain to be filled. Approaches to incorporate species and structural diversity and examining how carbon forestry techniques that balance both sequestration and storage with acceptable yields of sap on a per-acre basis will be important in the near term.

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Good Silviculture will Increase Productivity and Value over Time: A 72-Year History in a Northern Hardwood Forest

Kevin Evans¹

Abstract.—A 27,000-acre forest in northern New Hampshire provides a case study for evaluating the long-term outcomes of silvicultural prescriptions and cutting practices on forest growth and quality. This 214-year ownership has harvested timber since 1828 and maintained inventory data since 1947. The hardwood inventory data collected in 1947, 1967, 1986, 1998, and 2018 indicates that the practice of sound silviculture has not only upgraded products for increased value but has increased overall productivity allowing an increased sustainable yield. The study considers how exploitive cutting and diameter limit cutting in the early years led to a significant decrease in sawlog volume and an increase in pulpwood volume. The changing of silvicultural practices, in the late 1980s, to a single tree and group selection method, resulted in improved residual volumes of sawlog and decreases in pulpwood volume. Comparisons of consecutive hardwood inventories since 1947 show a significant increase in the amount of hardwood sawlogs and decrease in the amount of pulpwood on the property.

INTRODUCTION

In heavily forested rural areas, it is important to practice excellent forestry to cultivate high quality hardwood forest products to provide a continuous resource for a robust hardwood sawmill industry. Poor management practices, such as overcutting, creates declines in resource availability, reduces healthy habitats for wildlife, and pushes owners to capture nonforest product-based values (renewable energy development [windmills] and real estate values). This entire region has experienced a decrease in sawlog potential in the northern hardwood forest for years. Presently there is much consideration about rehabilitation of these forests following exploitive practices instead of a focus on good management to maintain high stocks of sawtimber stands.

The Second College Grant property (hereafter referred to as “the Grant”) owned by Dartmouth College has been utilized for timber since the mid-1800s. Inventories have been performed periodically on this forest since 1947; cruises were completed in 1947, 1967, 1986, 1998, and 2018.

METHODS

To prepare a fair analysis of impacts to hardwood stands from our treatments, past inventories had to be adjusted to make them comparable with current. First, all hardwood sawlogs and pulpwood volumes from all hardwood species were combined into a total volume (thousand board feet; MBF) and number of cords for the individual cruises, with no regard to individual species and/or products. This created a total number of board feet of logs and cords of pulpwood for the previous inventory. Harvest history data were then analyzed to determine the cutting methods used during that decade; detailed cutting records have been kept since 1970, while data for the 1950s and 1960s were found in harvest history maps and confirmed through conversations with foresters familiar with the Grant during this time period. Of note, hardwood harvesting was suspended from 1975

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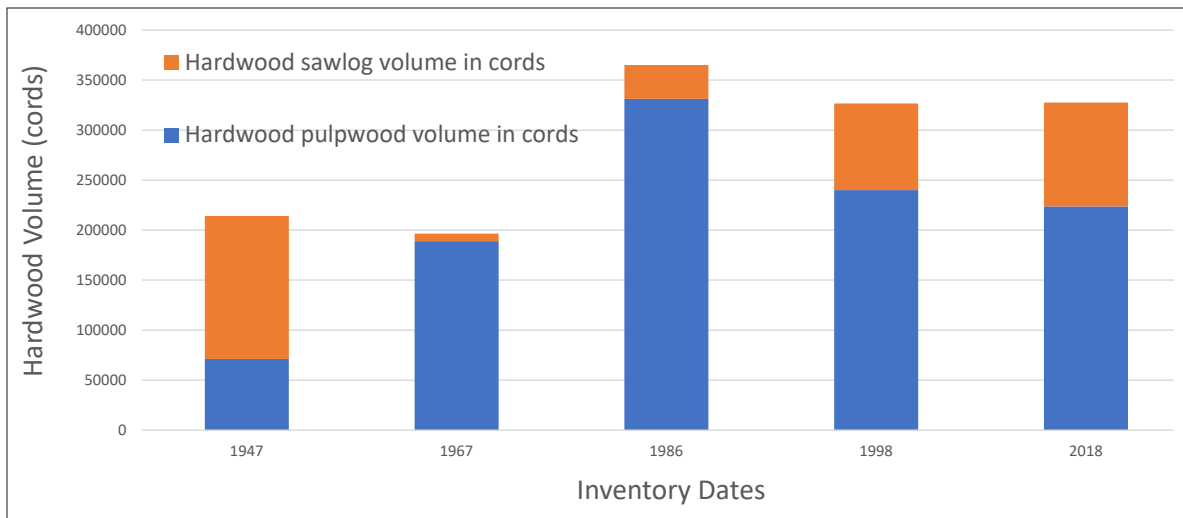


Figure 1.—Hardwood volumes (in cords) for both pulpwood and sawlogs 1947 to 2018.

to 1985 due to a severe spruce budworm outbreak, which led to a concentration of management efforts on the Grant's softwood resources.

In 1998, an inventory was designed to utilize log descriptions based on diameter and clear faces rather than any year's current commercial specifications. Inventories prior to 1998 were stratified by merchantable products at the time of inventory and used inconsistent product codes over time, which limited the ability to describe the development of species and product classes over time. The 1998 and 2018 cruises were redesigned using a 15 × 7.5 chain grid over the entire property (1803 plots) for easy replication every 20 years. Consistency between the 1998 and 2018 cruises in plot locations, sampling protocols, and inventory software, allowed for a more indepth analysis of changes in forest conditions across the Grant over these two decades.

RESULTS AND DISCUSSION

Mid-20th century treatments in the hardwood stands at the Grant included removal of large volumes of mature trees using diameter-limit cutting and sawlog-only harvests. This is evidenced by a significant reduction in hardwood sawlog volume between 1947 (at 77 million board feet; MMBF) and 1967 (at 3 MMBF), while pulpwood volumes increased from 71,000 cords to 188,000 cords during that same period (Fig. 1). All volumes refer to residual volume on property at time of inventory. This approach continued through 1987, although most cutting was diameter-limit treatments (14 inches and up); however, volumes were low enough at this time to see increased growth back into sawlogs (16 MMBF) and an increase in pulpwood to 330,000 cords. These overall trends indicated sawlogs were solely being harvested with pulp left behind.

In 1986 the College hired a full-time forester and wrote a new management plan. That plan mandated management focused on a reduction in the volume of hardwood pulp and an increase in sawlog volumes. The same focus was repeated in the plan revision in 2000. Most of the cutting was designed to improve the percentage of hardwood sawlog volumes while reducing pulp volumes. Harvest volume goals were 10,000 cords per year from 1986 to 1996 and then reduced to 7500 to 8000 cords for the period 1998 to 2008. Silvicultural prescriptions required the stands to be marked to a basal area of 75 to 85 ft²/acre following a desired diameter distribution with an additional goal to retain as many sawlogs as possible with a planned return interval of 20 years. Most harvests (80 to 85 percent) were single-tree and group selection cuts (openings no larger than one-half acre) with some small (average size 2 acres) clear cuts.

Table 1.—Inventory data for hardwood volumes by product 1998 and 2018 inventories

Product	1998 Volume	2018 Volume	Change
Veneer	1,034.3 MBF	2,696.2 MBF	1,661.9 MBF
Sawlog 1	7,530.5 MBF	4,814.4 MBF	(2,716.1) MBF
Sawlog 2	22,821.7 MBF	22,008.3 MBF	(813.4) MBF
Pallet logs	9,006.1 MBF	20,109.1 MBF	11,103.0 MBF
Pulp	240,067.0 cords	222,859.4 cords	19,948.4 cords

The inventory data from the 1998 and 2018 cruises show how successful treatments have been at increasing hardwood sawlog volume and reducing hardwood pulpwood volume. In 1998, hardwood sawlogs had grown to 40 MMBF and pulpwood was reduced to 240,000 cords. This trend continued through 2018 with sawlog volumes increasing another 10 MMBF and pulpwood reduction to 223,000 cords. This translated to an average volume increase from 18.6 to 20.6 cords per acre, or an increase of 19 percent in hardwood sawlogs. Figure 1 shows the inventory data split between sawlogs and pulpwood.

Further comparisons between the 1998 and 2018 volumes indicate that veneer volume (logs 11 inches d.b.h. with four clear faces) went from 1.0 to 2.6 MMBF over the 20-year period (Table 1). Sawlog 1 (logs 14+ inches in diameter with three clear faces) volume decreased significantly, from 7.5 MMBF to 4.8 MMBF. This may be due to a high mortality rate of some of the larger trees that were carried past rotation to ensure adequate stocking in that portion of our target diameter distribution (based on Arbogast structure). In particular, hardwood mortality rates, estimated from a concentrated set of CFI plots, was 0.345 cords per acre per year in 2003, but this was reduced to 0.154 cords per acre per year in 2018. Sawlog 2 is defined as logs 10 inches in diameter or greater with two clear faces. Logs in this product category have stayed relatively stable through the years. There is a small hump in the diameter distribution for this size class reflecting its stability. The stability in this class may reflect the reluctance of foresters to mark good quality 8- to 12-inch trees since they can anticipate further growth and increased value in the future. Pallet logs are defined as 8+ inch trees with at least one clear face. Pallet volumes have increased dramatically, likely due to sapling ingrowth into the pallet size class. These number should balance themselves out over time as some of the 8- to 12-inch trees grow into the sawlog 1 size class. The other trend that is still rewarding is the overall reduction in our pulpwood volumes from ~240,000 cords to ~223,000 cords, all the while keeping the same hardwood volume on the property as we had in 1986 when we started using these silvicultural practices. During the inventory period from 1998 to 2018, 130,000 cords of sawlogs and pulp (both hardwood and softwood volume) were harvested at the Grant. Table 1 presents all hardwood products in a comparison of the 1998 and 2018 inventories.

CONCLUSIONS

This case study provides strong field evidence that good forestry does increase value over time. Mid-century high grading and sawlog-only cutting had greatly reduced volumes and values between 1947 and 1986. As soon as the correct silvicultural practices were applied to the right acres, significant volumes, value, and productivity increased. The hardwood resource in 1947 (hardwood volume divided by total acres) was 8.1 cords per acre and it has increased to 12.0 cords per acre in 2018. Growth rate in 1967 (first time there is a growth rate reference in management plan) was 0.158 cords per acre per year, whereas it was 0.210 cords per acre per year in 2018. In the period from 1998 to 2018, 60,000+ cords of wood were added to the total volume at the Grant.

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Future Stand Development and Economic Consequences of Single-Tree Selection

Forrest M. Gibeault, Martha J. Sebald, and Richard W. Congdon¹

INTRODUCTION

The tree selection method for harvesting during all-aged management in the northern hardwood forest type has been well studied on research forests throughout the Lake States region. Many of these methods, developed in the 1950s, have been widely accepted and implemented by foresters who are working to develop quality sawn hardwood products. More recent research has indicated that forest managers are not always applying these all-aged approaches explicitly. Moreover, in many cases, the resulting stand conditions found in the years following individual tree selection practices do not result in the conditions anticipated by the forester.

Recent work completed by Steigerwaldt Lake Services LLC (Tomahawk, WI) as part of the Wisconsin Forest Practices Study (WFPS) evaluated alternative marking scenarios from tree inventory data collected on county, state, and private lands enrolled in the Wisconsin forest tax law programs (for more detailed explanation, see https://councilonforestry.wi.gov/Documents/PracticesStudy/6522%20WFPS%20NorthernHardwood_Modeling_12.01.2020.pdf).

In this paper, we review varying maximum tree size criteria and residual stocking generally following the single-tree selection method. These approaches were simulated into the future using FVS (forest vegetation simulator) and a custom model over a series of entries. Future stand structural elements and the present value of the forest products are compared to evaluate the sustainability of various tree selection approaches.

METHODS

This study utilized data from nine 1-acre plots (three plots per landowner class: county, private, and state) captured in 2015 as the baseline data, using the alternative harvest model previously developed. Eligible stands included those typed as northern hardwood forest, dominated by the sawtimber-size class, and managed under all-aged silviculture. Using the 1-acre plots provides a total sample size of 1,752 trees (trees 5 inches d.b.h. and larger), which provided a robust sample for the comparative modeling.

Two alternative selection scenarios were applied to each study. Each alternative marking scenario was primarily defined by maximum tree size and residual basal area (BA). These approaches are presented below.

- Scenario 1: Maximum tree size = 17 inches d.b.h. Residual BA of 75 ft² per acre
- Scenario 2: Maximum tree size = 19 inches d.b.h. Residual BA of 82 ft² per acre

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The “cut” versus “leave” designations were determined using a tree selection model built in Microsoft Excel®. Trees were prioritized for harvest based on three indices: removing risk (Index 1), harvesting mature trees (Index 2), and releasing crop trees (Index 3); harvest criteria were applied in this order of priority. Each index had an associated formula to determine the tree’s ranking, which was independently applied to each tree. Trees that received higher ratings were prioritized for harvest first. Selection was determined between trees of equal rating using the random number applied to each tree.

In the selection model, a proportion of total BA to be harvested (current BA minus residual) was assigned to each rule. The rules focused on removing trees classified as having high risk (60 to 65 percent of the BA), meet conditions to be considered mature (17 to 19 inches d.b.h., 25 percent of the BA), and release of crop trees (10 to 15 percent of BA).

Future stand conditions were modeled and used to test the viability of the alternative harvest scenarios developed in the 2016 study. FVS regeneration requires custom settings in many cases. Considering challenges throughout the Lake States with northern hardwood regeneration due to deer herbivory, gap success, and invasive competition, among other constraints, we chose to control how FVS established regeneration following silvicultural treatments. We chose intentional natural “planting” keywords in FVS to trigger tree regeneration using assumptions derived from northern hardwood research (Knapp et al. 2019) coupled with dominant tree stocking from the plot data.

For the existing marking scenario, or Scenario 0, tree growth and harvest prescriptions are completed in FVS. Following the initial cut in 2015, the residual tree list was grown in FVS through 2075. There were three cuts performed in 2035, 2055, and 2075. Seedling regeneration was introduced 5 years following harvests in 2020, 2040, and 2060. Five years after regeneration seedlings were introduced, the model included adjusted mortality settings in FVS to introduce 99 percent mortality for white ash and 65 percent for sugar maple, which was focused in the 1- to 4-inch diameter classes. Mortality was added to the model in 2025, 2045, and 2065. This research effort evaluated the following scenarios:

- Scenario 0 (existing marking scenario, or base case): existing marking condition modeled forward using FVS single-tree selection harvest treatment, following the Q-factor method
- Scenario 1: applied Scenario 1 alternative tree selection model for harvests and FVS between treatments
- Scenario 2: applied Scenario 2 alternative tree selection model for harvests and FVS between treatments

RESULTS

The projected harvests modeled (Table 1) using the alternative harvest approaches produced greater total present value of harvest revenue in all ownerships for Scenario 1, while Scenario 2 was higher on state and private lands when compared to Scenario 0 (the projected existing stand condition sampled in 2015).

The residual forest stumpage value in 2075 averaged 2 percent higher in Scenario 1 and 3 percent lower in Scenario 2 when compared to Scenario 0.

The residual forest structure of the scenarios differs more over time, resulting in a final forest condition in 2075 where Scenarios 1 and 2 carry ± 30 to 56 percent more sawtimber on two of the three ownership classes compared to Scenario 0.

Table 1.— Value at present (2015) and projected values based on alternative harvest approaches

All Cuts (2015 Dollars)	
County	Value Per Acre
Scenario 0 - Cut	\$988.89
Scenario 1 - Cut	\$1,145.61
Scenario 2 - Cut	\$919.25
Private	Value Per Acre
Scenario 0 - Cut	\$780.52
Scenario 1 - Cut	\$1,029.15
Scenario 2 - Cut	\$797.26
State	Value Per Acre
Scenario 0 - Cut	\$981.81
Scenario 1 - Cut	\$1,340.87
Scenario 2 - Cut	\$1,207.64

CONCLUSIONS

Harvest volumes of both poletimber and sawtimber varied across the model period. However, harvest value was found to generally increase with time. While the alternative harvest scenarios focused on removing larger trees, the model suggests that the approach can be sustained over time without compromising future harvest opportunities.

The study suggests that alternative harvest approaches that focus on tree quality and economics with less focus on stand structure can produce long-term sustainable forest conditions that do not jeopardize forest harvest potential and sustainable tree stocking levels.

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Using Irregular Shelterwood Systems to Optimize Value Growth in Southern Ontario Maple Forests

Peter A. Williams¹

INTRODUCTION

Many shelterwood variants use even- and uneven-aged concepts to manage stands with complex or patchy structure. It can take a skilled practitioner to prescribe, apply, or discern the system or hybrid being used, (e.g., single tree selection (STS); thinning, continuous cover (CC), group selection, irregular shelterwood (IS), expanding gap; and/or extended irregular shelterwood (EIS). This presentation will discuss the southwestern Ontario situation, IS systems and their application, and four case studies in exceptional stands with histories of good forest management (GFM).

IS (e.g., Femelschlag, Plenter systems) has been used worldwide for many years and is best documented in European literature (e.g., Troup 1928). Raymond et al. (2009) reviewed IS describing many applications, suggesting that the group of variants can be used to restore degraded forests and manage forests with irregular structure.

EIS and CC approaches scaled from individual tree to stand or woodlot have been used by the author to optimize/maximize value and volume growth while maintaining forest and ecosystem integrity and aesthetics. These approaches are particularly useful in managing heterogeneous stands of even-aged patches, influencing regeneration development with maturing upper canopy over multiple stand entries, optimizing revenue over time. A simple example of CC would be converting a conifer plantation to natural forest, where regeneration is started, manipulated, and released over a number of entries, resulting in scattered large conifers over a “natural” forest.

APPROACH

The author has used a combination of IS approaches as a primary strategy to manage private woodlands in southwestern Ontario since 1996. Southwestern Ontario is an agricultural landscape with some excellent site quality, valuable hardwoods, and variable woodlot size, similar to much of the midwestern United States. Upland forests are often dominated by sugar maple (*Acer saccharum*; Mh), and lowland deciduous forests are often dominated by red or silver maple (*Acer rubrum*, *A. saccharinum*), and/or ash (*Fraxinus* spp.). Most stands originated after historic heavy cutting or abandonment by agriculture, often resulting in complexes of even-aged patches, even in very small woodlots.

In upland stands with high quality sawlog and veneer potential (e.g., Mh, red oak [*Quercus rubra*; Or]), the IS approach can foster the development of trees with the highest value growth potential to optimize value growth over time. The author has estimated that the value growth for veneer-potential trees without height-limiting defects range from 15 to 25 percent per year for trees from 13 to 18 inches diameter at breast height (d.b.h.). In general, managing these stands for income should focus on increasing the proportion of veneer potential trees and harvesting them as their grade-value growth declines.

The approach also works in lowland stands because they tend to have lower value species without a significant grade premium. In these situations, the approach emphasizes volume growth per tree

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Table 1. —Four case studies in southwestern Ontario woodlands, showing woodlot size, entry years, nominal return and present net value (PNV) of annual and total revenue/acre/year for each woodlot

Case Study	Area (Acres)	Entries (years)	Nominal annual return/acre (\$CAD/US)	2021 PNV (\$/acre/year and Total revenue)	
				\$CAD and \$US (5% IRR) \$CAD/acre/yr & total	\$US/ acre/yr & total
1	13	1980, 1989, 1998, 2005, 2016	\$494/\$396	\$1,191/\$278,625	\$956/\$223,776
2	45	1999, 2001, 2003, 2004, 2007, 2014, 2018	\$434/\$349	\$818/\$699,098	\$657/\$561,525
3	17	2000, 2006, 2020	\$520/\$418	\$1,069/\$363,311	\$657/\$291,707
4	35	2004, 2020	\$432/\$347	\$860/\$511,528	\$691/\$410,866

(i.e., tree form and density) rather than grade. It can also be used in rehabilitating degraded upland forests because diameter-limit distribution requirements do not apply, allowing the marker to focus on improving tree quality rather than STS requirements for retaining specific stem numbers for each diameter class. This also stimulates growth and development of vigorous regeneration.

Four case studies of sugar maple-dominated forests with a history of GFM are described below. Most GFM at the sites began in the 1980s through Ontario Ministry of Natural Resources (OMNR) extension programs.

GENERAL SITE DESCRIPTIONS

The four sites were dominated by sugar maple; well stocked with large, high quality stems on excellent sites (Mh SI of 100 ft or higher at 100 years); and well managed by owners with a positive stewardship approach. Stands 1 and 3 were over 80 percent sugar maple and Stands 2 and 4 were 60 percent Mh with Or, black cherry, and other northern hardwood associates. Our initial entry used the CC approach with follow up entries incorporating an expanding-gap component. The stand densities went from 104–113 ft²/acre (24–26 m²/ha) to 83–91 ft²/acre (19–21 m²/ha).

Each entry considered biodiversity and the retention of important cavity trees. Each site had some trees with 20 meter or greater merchantable height (25 cm top). Income from the harvests was clearly dependent on earlier improvement thinning. Harvests in the 1980s had established desirable regeneration through the stands. Table 1 provides summaries of the income from each woodlot, including present net value in Canadian and U.S. dollars.

CASE STUDY 1

The woodlot is a 13-acre sugar maple forest with a patchy complex of three even-aged conditions: large older trees over sapling regeneration, even-aged small sawtimber, and single-aged sapling regeneration. It had been marked and harvested in 1980 and 1989 through OMNR extension programs and had very good growing stock.

Williams and Associates (W&A) marked the stand in 1998, 2005, and 2018 using IS prescriptions, conducted canopy thinning/partial release cut in two-aged parts, improvement thinning/harvest in small sawlog areas, and expanding gap in openings with saplings. There has been excellent growth and overall grade improvement and patches of smaller trees have developed into a canopy of high quality maple, many with veneer potential. The stand will be assessed in 2025 to plan for the next harvest. The nominal annual net return since 1998 was \$494/acre/year CAD.²

² Canadian dollar.



Figure 1.—Inspectors at Case Study 3 (2020) with long, clear logs with small hearts. Courtesy photo by Peter A. Williams, used with permission.

CASE STUDY 2

Grandad purchased this 45-acre farm woodlot in 1912 and the family managed the woodlot with some advice from foresters until 1997. W&A began working with the owners in 1998 when the stand was a complex of single and two-aged patches, some with denser canopies and little regeneration to gaps overstocked with small saplings, and stages in between. Most areas were dominated by medium or very large (24 to 36 inches d.b.h.) sawtimber and areas with significant components of higher concentrations of red maple, ash, or beech (*Fagus grandifolia*). The canopy included spectacular individual Mh, Or, and white pine.

A series of eight harvests were conducted using IS approaches between 1999 and 2018, three “comprehensive” harvests and five targeted entries (Table 1). The targeted entries included salvages of blowdown, beech, or ash. Three recent entries were to spread income and incorporated the expanding gap approach in some older openings. The nominal annual net return since 1999 was \$434/acre/year CAD. The woodland remains well stocked with quality trees and will be reassessed in 2028.

CASE STUDY 3

A 17-acre farm woodlot was marked by the OMNR in 1982 (no information available). In 1999 the woodlot was primarily a two-aged stand, dominated by large sugar maple of exceptional quality (Fig. 1) on a very productive site. There were some areas with scattered ash, beech, and Or.

W&A implemented comprehensive harvests in 1999 and 2020 and a smaller harvest in 2006 to clean up storm damage. The 2020 entry started some expanding-gap aspects. The nominal annual net return since 1999 was \$520/acre/year CAD. The woodland remains well stocked with high quality trees and is scheduled to be reassessed in 2030.

CASE STUDY 4

A 35-acre farm woodlot was marked by the OMNR in 1982 (no information available). W&A implemented harvests in 2004 and 2020. In 2004, the stand had large single- and two-aged patches on variable (i.e., some deep soils and others shallow to bedrock) but mostly very productive sites.

Patches ranged from single-aged polewood/small sawtimber sections to two-aged with very large sawtimber over dense sapling regeneration. In many areas, seedling and sapling cohorts had developed after the 1982 harvest. The forest was dominated by good to excellent Mh, with an exceptional Or component. In the 2004 harvest, at the height of timber values, the Or averaged 482 bdft/tree. Other species included ash, beech, and black cherry (*Prunus serotina*).

The two harvests were conducted using IS approaches and the nominal annual net return since 2004 was \$432/acre/year CAD. The woodland is scheduled to be reassessed in 2030.

CONCLUSIONS

In summary, commercial harvesting practices like high-grading or diameter limits have left many forests with degraded growing stock and limited value growth potential. Applying any GFM strategy will improve forest and tree quality and value growth. However, IS approaches are particularly useful in managing for high quality individual trees of all sizes, improving their immediate growing conditions and value potential rather than focusing on balancing diameter distributions over the whole stand using STS.

IS approaches require astute and intuitive planning and tree marking and familiarity with felling and harvesting practices. Like STS, IS can provide for continuous forest cover and harvests over time. However, applying an STS approach onto an even-aged structures can result in damaging, prematurely harvesting, or limiting the development of high quality trees. Careful harvesting with monitoring using IS approaches can result in less damage to residuals, higher production of grade sawlogs and veneer, more vigorous regeneration, and less administration than STS. Targeted entries to manage cohorts in even-aged patches/clusters within a stand can foster the development of desired high value trees (i.e., for timber value, wildlife habitat, diversity) by focusing on conditions in each patch.

These exceptional returns from harvests are clearly the result of good historical management. W&A manages many woodlots on equally good sites that have been degraded by commercial harvesting practices, and many are recovering well. The four subject woodlots remain well stocked with high quality canopy trees and developing younger age classes and should remain similarly profitable in the future.

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Internal Rate of Return of Sugar Maple (*Acer saccharum*) in Wisconsin

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Management of sugar maple (*Acer saccharum*) has the primary objective of growing trees that will produce high quality wood (Germain et al. 2015). As such, forest management often prioritizes the release of crop trees. However, in order to produce high value logs, there is an investment cost in the amount of time it takes for a tree to reach a desired size. Additionally, the collection of landowner goals, only some of which are economic, strongly impact management decisions. In species such as sugar maple, the length of time required to meet the basic specifications for sawlogs is sufficiently long to result in a rather low internal rates of return compared to many other species.

Dey et al. (2017) found that larger trees produced the highest value due to increase in volume and grades in the second and third logs. However, when age was taken into account, trees older than 100 years had a lower value than younger trees. This result implies that there is a certain point in a tree's life where its value begins to decline, regardless of its continued increase in volume. The purpose of this study is to estimate and analyze the internal rate of return for sugar maple over a 10-year period to determine how the tree's value (with all potential risks or changes in grade ignored) changes during that time.

The sites used for this study were eight northern hardwood stands in northern and central Wisconsin that were actively being logged during 2018. While composition varied between sites, sugar maple was generally one of the dominant species. Overall, these sites varied in quality and management history; however, it is likely that all had been subjected to a hard selection harvest one or more times in the past. A subset of data from a previous study (Kaminski et al. 2019) was also included. At each site, a maximum of 10 sugar maple trees were selected and measured before and after being cut and merchandized.

For each standing tree, the following data were collected:

- Diameter at breast height (d.b.h., to nearest 0.1 inch)
- Average width of the crown by measuring the width of the crown (to the nearest 1 foot) in two directions
- Height to the live crown
- Total height
- Standing tree grade for the best 12 feet of the lower 16 feet following Great Lakes Timber Professionals Association guidelines (GLTPA 2016)

After the standing trees were measured, the trees were cut and merchandized by the loggers using normal protocols to optimize recovery of high quality logs. The resulting logs were scaled and graded following the GLTPA grading guidelines into grades 1, 2, or 3. A log that fell below grading guidelines for either scaling diameter or quality was assigned a below-grade status (grade 4, henceforth).

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Table 1.—Proportion of logs assigned to a specific grade for merchandized pieces (1-4) harvested from each tree

Grade	Log 1	Log 2	Log 3	Log 4
Grade 1	0.20 (n=15)	0.06 (n=4)	0.00 (n=0)	0.00 (n=0)
Grade 2	0.51 (n=38)	0.51 (n=34)	0.31 (n=15)	0.40 (n=6)
Grade 3	0.26 (n=19)	0.33 (n=22)	0.51 (n=25)	0.47 (n=7)
Grade 4	0.03 (n=2)	0.10 (n=7)	0.18 (n=9)	0.13 (n=2)

Table 2.—Calculated internal rate of return percentages for sugar maple logs over the past 10 years sorted by grade (1-4) and diameter size class, in inches

D.b.h.	Grade 1	Grade 2	Grade 3	Grade 4
≥13 (≥12.1 - 14)	14.6%	3.1%	4.4%	2.8%
15 (≥13.1 - 16)	7.8%	5.5%	2.2%	2.8%
17 (16.1 - 18)	x	3.1%	4.6%	3.1%
19 (18.1 - 20)	2.1%	3.3%	2.3%	2.6%
21 (20.1 - 22)	3.0%	2.9%	2.2%	x
23≤ (22.1 - 24)	2.5%	x	2.5%	x

Internal rate of return for each log was calculated by comparing the current value of merchandized logs to the value they would have had 10 years prior. In order to estimate the past volume for these logs, we used the growth measurement taken by measuring the rings over the past 10 years on each end and subtracting it from the radius. Then the volume of each individual log, both current and 10 years ago, was calculated using the assumption that the same merchandizing decisions would have been made 10 years ago and at the time of actual harvest. Delivered prices for each product class were determined by using values provided by the 2012 Timber Mart North price report – Wisconsin edition (Prentiss and Carlisle 2012) (the last year that delivered prices were estimated for this publication) and inflating the prices to meet current specifications (U.S. Inflation Calculator 2018). Estimated cut-and-haul costs (Gibeault and Coutu 2014) were adjusted for inflation and then subtracted from adjusted delivered values to determine stumpage price. Any physical damage or abnormality was assumed constant over this 10-year time frame, as there is no accurate method of determining what features the tree had at the time. This provides the assumption that logs from 10 years ago were assumed to have the same grade unless they failed to meet the specific size specifications. We were able to use the calculated volume and grade for the past and the present logs to determine the value for each. The internal rate of return (IRR) function in Microsoft Excel® was utilized to predict the percent return for each log.

An analysis of individual log pieces found that almost 80 percent of all grade 1 logs were in the first merchandized piece of a tree. The results show that quality tends to decline as you move up from the first merchandized piece (Table 1). The results for the IRR calculation (Table 2) indicated that there was value growth (\$/MBF) when trees changed product class from a bolt to sawlog. Trees with grade 1 sawlogs had the most notable increase, with IRRs as high as 14 percent.

Lower grade trees were much less effective, with IRR values falling short of 5 percent when they improved to the next higher product class. The data demonstrated a significant decrease in IRR for each tree as its diameter increases, specifically for those with grade 1 potential. Change in IRR for trees with lower grades was less impactful than trees with grade 1 sawlogs. This seems to indicate that the value the tree accumulates each year begins to decrease once it reaches a specific size class.

Management decisions made to optimize a tree's financial return within a site are often determined by considering factors related to a tree's ability to accumulate value upon the next stand entry. Of course, financial return is only one of the collection of landowner goals; however, this does strongly impact management decisions. A common practice in Wisconsin is to grow trees, particularly those with potential for quality sawlogs, to larger sizes to maximize the potential of the tree. Once a log reaches a specific size class within a tree, its value drastically increases. Each log within the tree can increase to a higher product class once its small-end diameter reaches a specific size. This effectively means that the longer a tree is left growing on site, the higher the chance it has to produce more valuable products.

Our study found that from an economic perspective, the IRR for sugar maple logs has a tendency to decrease as its diameter increases (Table 2). This is particularly noticeable for grade 1 sawlogs, which show an IRR of around 14.6 percent at the 13-inch size class down to around 2.5 percent at the 23-inch size class. The data suggest that the potential for these logs will only decrease once they have reached highest value product class. Once a good quality tree has reached the point where it can no longer increase to a higher product class, it should no longer be considered for retention unless it is needed to meet other goals for the site (for example, maintenance of adequate basal area).

Dey et al. (2017) found that older trees can compensate for risk by increasing the value in the second and third logs in the tree. Because 40 percent of the tree's total value comes from the first log, the risk of letting the upper logs in the tree grow to grade 1 or veneer is even higher. However, during our study we found that certain trees that had a defective first log were selected as crop trees because of the potential value that could be obtained by the second and third logs before the next harvest. The value of the first log would likely not improve significantly, but if the second or third log could improve to grade 1 or veneer through time, then retention may be logical.

One assumption of this project is that log grades do not decline through time. Webster et al. (2009) has shown this to be inaccurate. We have intentionally not included risk through time within this model. We chose this approach because the composite risk associated with an individual tree is very difficult to determine and is partially dependent on each organization's goals and objectives, and these include financial risk (for example, value of the species in the marketplace may decline) and physical (for example, the tree may be damaged or die). While determining the value of risk is an important part of an organization's mission, it is outside the scope of this project.

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Maximizing Value of Timber Resources in Northern Hardwood Forests: Log Sorting in Wisconsin Timber Sales

Shuva Gautam, Adam Wysocki, and Baburam Rijal¹

Abstract.—Northern hardwoods produce a variety of logs suitable for different final products. It is generally understood that sorting logs based on grade generates maximum value for all stakeholders. However, the benefits of log sorting may depend also on the geographical distribution of forest stands and manufacturing mills. The objective of this study was to evaluate the profitability of log sorting based on geographical location of forest stands, destination mills, and market parameters. A decision-support tool was used to allocate logs from timber sales to highest-profit-yielding mills. Factors considered by the model included logging cost, transportation cost, stand's distance to mills, mills' acceptance criteria, and price at the mill gate. Four small scale timber sale tracts from across Wisconsin were selected for the study. Several scenarios were tested with each scenario yielding different mixtures of log grades. The results showed that log sorting increased profit by up to \$11.33·m⁻³ in certain locations but was not profitable in other locations. The methods proposed can help practitioners and landowners increase the monetary value and utilization of timber. Practitioners should systematically analyze forest stands to determine the gain or loss in profit resulting from sorting logs. Implementation of the proposed tool will help increase the use of under-utilized timber, especially in areas where profits are marginal.

INTRODUCTION

Wisconsin forests contain many different species in a single stand that may be managed using even- or uneven-aged silvicultural practices. Such stands contain logs that are suitable for manufacturing a variety of forest products. The task of sorting logs is important given the significant amount of profit that could be lost if done incorrectly (Dramm et al. 2004). For example, veneer logs of certain species can yield over \$1000/MBF² and the price for log grade 1 can drop precipitously to less than \$500/MBF. However, studies have demonstrated that logging cost increases with the number of log sorts (Manner et al. 2013). This can be attributed to the inefficiencies due to additional time taken by operators to sort logs. Logs will need to be sorted either at the felling site or at the landing. Sorting logs at the felling site will reduce the productivity of the harvester, the forwarder may also need to transport the different piles separately, increasing the number of trips. Higher number of sorts will also require larger landing area whether it is sorted at the felling site or at the landing site. All this ensemble will reduce productivity significantly. Therefore, log sorting decisions need to be made judiciously, otherwise it could lead to a net loss. The decision to sort logs is not straightforward because it is influenced by a number of supply-chain parameters and market conditions. The location of timber sales is a major factor that influences the profitability of sorting logs. If the mill is beyond a certain distance, it may not be profitable to sort a particular grade even if the price paid at the mill is high. Transportation cost can be a highly influential factor. Such decisions will not be obvious in all scenarios in all

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² MBF = thousand board feet

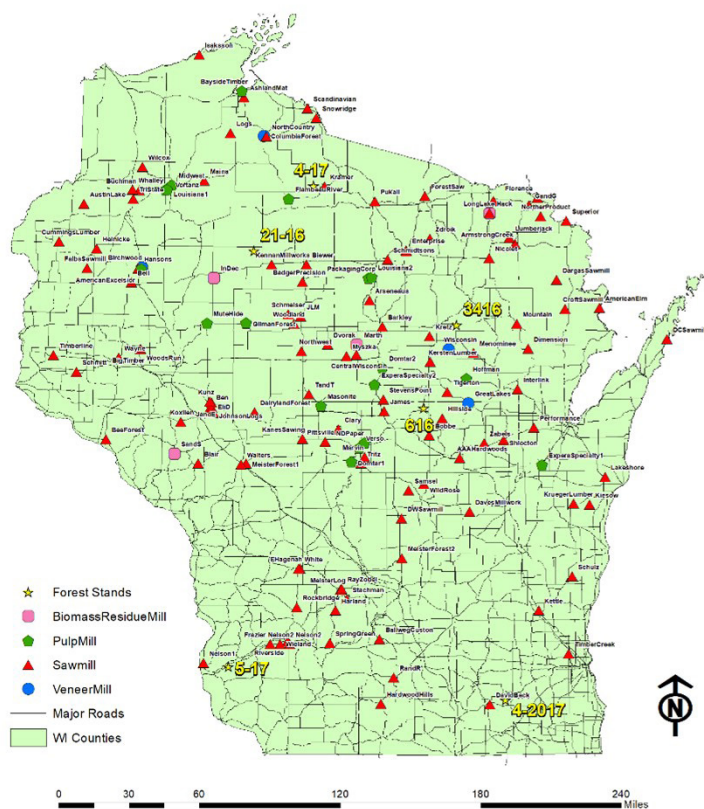


Figure 1. —Map of the study area showing mill and harvest site locations.

locations across Wisconsin. Making an optimal decision can be quite complex when taking into consideration various factors, such as the number of log sorts, the prices paid at the potential mills, and distance to each of those mills. Regardless, such decisions are made by practitioners without the use of any analytical tools. The objective of this study is to quantify the potential profit or loss associated with log sorting at various locations across Wisconsin.

METHODS

Data from several different timber sales that occurred on Wisconsin state lands were used as the supply data for this study. The data contained location of the timber sale tracts and volumes by species. Four different locations were selected to represent different supply and market dynamics within the State. Volumes were further categorized into pulpwood, biomass, sawbolt, and grade logs. Three hypothetical scenarios were subsequently developed. Volumes of pulpwood, sawbolt, and biomass remained constant in all scenarios, but the volumes of graded logs were different. Scenarios 1 contained the largest proportion of higher grade logs followed by scenarios 2 and 3. The log grades included in the study were veneer, grades 1, 2, and 3. Mill location and data on their capacity were obtained from the Wisconsin Department of Natural Resources (Fig. 1). The data also contained information on the types of logs accepted by each of the mills. The ArcGIS Network Analyst extension was used to calculate the distance between each mill and the timber sale. A linear programming model was developed to allocate each assortment in each of the timber sales to a mill. The objective was to maximize profit through the sales of the logs at the mill gate. Costs taken into consideration included logging cost, transportation costs, and stumpage. The profitability of different log-sorting scenarios at various locations across Wisconsin were subsequently assessed.

Table 1.—Summary of results of the optimization process for different timber sale tracts and scenarios

Tract	Scenario	Total volume harvested (m ³)	Profit (\$)	Profit (\$/m ³)
Southwest	1	360	18,919	52.59
	2	377	22,423	59.49
	3	394	18,981	48.17
Central	1	1,030	18,546	17.99
	2	1,006	18,082	17.96
	3	1,023	12,944	12.65
Southeast	1	257	764	2.98
	2	411	1,222	2.98
	3	257	764	2.98
Northwest	1	7,613	23,838	3.13
	2	7,645	22,153	2.90
	3	7,614	19,640	2.58

RESULTS

A summary of the results is shown in Table 1. Although scenario 1 generated the highest proportion of high values logs in all scenarios, it produced the greatest profit in only two of the four scenarios. The tract in the Southeast region did not have many mills operating so there was limited choice regarding where the various log assortments could be sent. The lack of mills meant that only sawbolt was utilized although higher value logs were sorted. Southwest region tract was another case where scenario 1 did not generate the highest profit. This region produced the highest profit per cubic meter harvested due to the presence of high value trees such as walnut and cherry. The reason that scenario 1 did not produce the highest profit was because the region did not have veneer mills nearby where the highest value logs could be sent. Scenario 1 would have likely yielded the greatest profit if mills in other states were also included in the study. Nevertheless, the difference between scenario 2 and scenario 3 was over \$11·m⁻³ indicating that sorting was worth it in the tract.

The Central and Northwest regions yielded the highest profit for scenario 1, followed by scenarios 2 and 3. These timber sale tracts had a diversity of species and access to a variety of mills nearby that processed multiple products and species. Logs sorted in these regions were sent to as many as 11 mills. It was worthwhile to sort logs in these regions because each sort could be sent to a mill at a feasible transportation cost. The increase in profit in the Central region between scenario 3 and 1 was \$5.34·m⁻³, and just below \$2·m⁻³ for the Northwest region, which is relatively low but the quality of trees in the tract limited the profit.

CONCLUSION

Log sorting is an important task, particularly in northern hardwood forests that produce a range of log assortments that are suitable different types of mills. The right decision for each scenario depends not only on the species mix present in the forest but also on market conditions and location. This study demonstrates that there may be significant gains associated with using decision-support tools to make log sorting decisions. Such tools are particularly useful in areas with variety of mills and in areas that grow high value trees.

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At Which Diameter Does Sugar Maple Reach Financial Maturity at the Northern Edge of its Range?

François Guillemette and Filip Havreljuk¹

Abstract.—Improving financial revenues from partial cuts in sugar maple (*Acer saccharum*) stands at the northern edge of the species' range involves harvesting trees that have reached their financial maturity size (i.e., the diameter at which their monetary value is greatest and beyond which there is no further gain). To establish the lumber value of each tree at the sawmill, a sample of 171 trees were measured, felled, bucked into logs, and sawn into boards. We estimated their value changes over 10 years using data from a network of permanent sample plots. The most vigorous and best quality maples started losing value at a diameter at breast height of 36 cm. Those belonging to the lowest grade and containing a potential sawlog increased in value, but only marginally. The low value of these trees makes the profitability of forest management challenging at the northern edge of sugar maple's range.

INTRODUCTION

Sugar maple (*Acer saccharum* Marshall) is one of the most abundant hardwood species in eastern North America (Godman et al. 1990). Its primary range extends from 35° to 48° of latitude North, from the state of Tennessee (United States) to the province of Quebec (Canada). Sustainable management of sugar maple for timber production is challenging at the northern edge of the species' range, due to high transportation costs and low timber quality (Guillemette and Bédard 2019). In this region, maple stands are managed using partial cuts to mimic the natural dynamics of individual tree mortality in these forests.

Historically, the demand for sugar maple sawlogs in this region was low. Recently, however, the lack of volume available in the south of Quebec forced sawing activities to move further north. Improving the financial revenues from partial cuts involves harvesting more high quality maple trees that have reached their financial maturity size (i.e., the diameter at which their monetary value is greatest, and beyond which there is no further gain) and fewer low quality trees with defects. Size at financial maturity has been defined for trees growing in the southernmost portion of the sugar maple management area in Quebec (Guillemette 2016). The objective of this study was to determine the financial maturity size for sugar maple at the northern edge of the species' range.

MATERIAL AND METHODS

Calculating tree financial maturity size for the needs of the sawmill industry requires estimating the monetary value of trees at the beginning and at the end of a growing period, in order to identify the diameter at which a tree's mean value begins to decrease. This analysis relies on a model to estimate the value of lumber according to a tree's diameter, which is applied to trees whose evolution has been monitored over a period of time. The main monitored variables are survival or death, diameter growth, and stem quality change.

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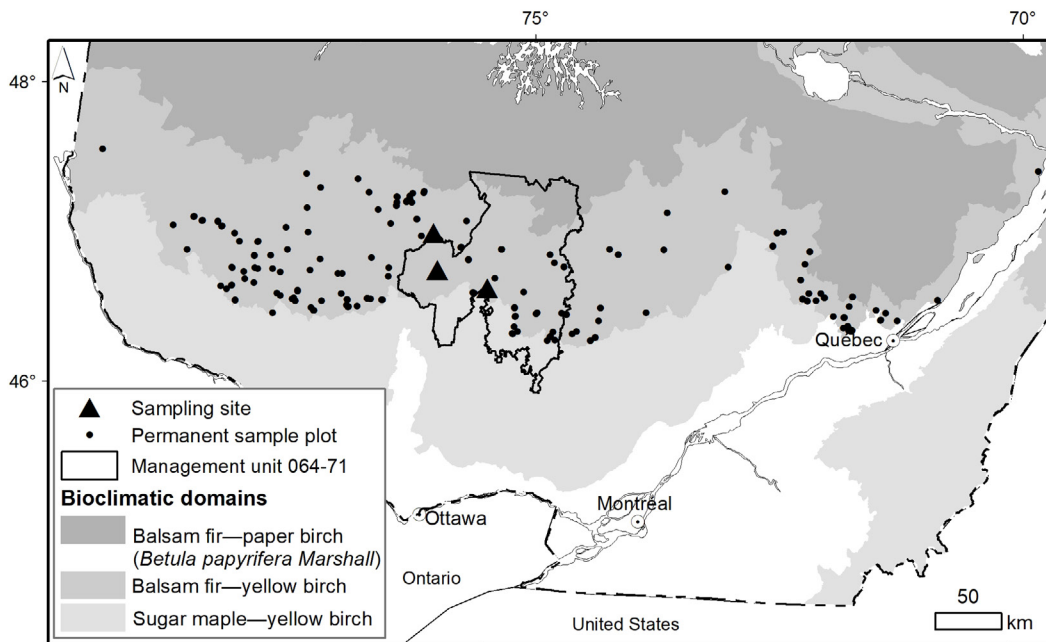


Figure 1.— Location of the permanent sample plots and the study sites within the balsam fir–yellow birch bioclimatic domain of the province of Quebec, and location of the management unit of interest.

Tree Value

We sampled 171 sugar maples in three northern sites located in or near a management unit of interest for the maple sawmill industry (Fig. 1). The sampling sites were located in the balsam fir (*Abies balsamea* [L.] Miller)–yellow birch (*Betula alleghaniensis* Britton) bioclimatic domain. In this northern territory, sugar maples are mostly located on top hills, while balsam fir and yellow birch dominate more mesic sites (Gosselin et al. 1998). Mean annual temperature varies from 0 to 2.5 °C, and mean annual precipitation ranges from 800 to 1,000 mm.

The studied trees were classified into four grades (A, B, C, and D, after MRNQ 1995), which correspond approximately to grades 1, 2, 3, and below-grade, respectively, in the system commonly used in the United States (Hanks 1976). This grading is established according to a tree's diameter at breast height (d.b.h., measured at a height of 1.3 m), length and number of defect-free sections on the surface of the second-worst face of the best 3.7 m log located on the butt log (first 5 m), and percent volume deduction for crooks, sweep, and rot within the log. Grades A (22 trees) and B (43 trees) have minimal d.b.h. thresholds of 39.1 and 33.1 cm, respectively, while grades C (80 trees) and D (26 trees) both have a minimal d.b.h. threshold of 23.1 cm. In this study, grade A and B trees were merged into an AB grade, both for simplicity and because grade A trees are relatively rare in the study area (Guillemette and Bédard 2019).

Once the trees were felled and bucked into logs, the 170 resulting sawlogs were sawn into 1,974 boards and blocks that were graded according to the NHLA (2007) classification. A complete tree-log-lumber tracking record was kept throughout the study, as described in detail in Bédard et al. (2018). Using the actual lumber trend prices for the study region (Table 1), we established the lumber value of each tree at the sawmill. We did not include the price of the unmeasured volumes for chips, sawdust, and bark.

Table 1.— Lumber trend prices according to grade and color (after NHLA 2007) estimated for sugar maple in the province of Quebec, Canada (\$ CAD/MBF). MBF = thousand board feet; CAD = Canadian dollar. Data source: Bureau de mise en marché des bois, ministère des Forêts, de la Faune et des Parcs du Québec (Quebec's governmental timber marketing office). Currency conversion: \$1 CAD = \$0.82 US as of May 6, 2021.

Grade	Price according to color (\$ CAD/MBF)	
	Sap	Regular
FAS & Selects	1,800	900
1C	1,325	700
2C	1,025	520
3C	875	475
3B	300	300
Central block	375	375

We calibrated a two-part conditional model (similar to that of Fortin et al. 2009) to estimate the average lumber value of a maple tree with a given d.b.h. and tree grade. In a first step, we estimated the probability of observing a sawlog in a given tree, and in a second step, we estimated the average value of lumber in this tree when at least one sawlog is sawn (analyses performed using the GLIMMIX and MIXED procedures, respectively; SAS Institute 2008). Finally, we calculated the mean lumber value in the tree by multiplying the probability of occurrence (first part) by the mean conditional value (second part) of the lumber in a tree.

Tree Value Change Over Time

To estimate the value change of each tree over a growth period, we used data from a network of permanent sample plots in the same bioclimatic domain and observed each tree's evolution as a function of its d.b.h., risk class, and tree grade. The risk class system aims to identify trees according to a gradient of mortality risk over the next cutting cycle based on the presence of defects on the tree (Boulet 2005). Trees were classified as moribund (M), surviving (S), growing to be conserved (C), or reserve stock (R) following a descending order of anticipated mortality risk: M trees are often characterized by the presence of a fungal infection, an abundant decay, or crown dieback; S trees are frequently associated with stem cracks or a small amount of decay; finally, C and R trees are considered sound and vigorous. C trees usually present some minor defects, such as a crook or sweep. In this study, C and R trees were merged into a CR class to simplify.

In the study area, measurements of risk class and tree grade were available since 2003 in Quebec's national forest inventory database (MFFP 2014), and since 2005 in datasets from experimental plots (Guillemette and Bédard 2019) and monitoring plots (Guillemette et al. 2017) of two study networks for selection cutting. From these data, we used a total of 2,000 sugar maple trees with a d.b.h. of 23.1 cm to 49.0 cm that were surveyed on average for 10 years (4 to 15 years) in 274 permanent plots (Fig. 1). Forty-seven percent of these trees were in a plot managed under a partial cutting system, mainly selection cutting.

We estimated the lumber value of sugar maple trees for every possible combination of d.b.h. class (2 cm increments from 24 cm to 48 cm), risk class (3 levels), and tree grade for lumber at the beginning and at the end of the growth period. We then calculated the mean annual change in lumber value for each combination. The limits of financial maturity for sugar maples belonging to the different combinations of risk classes and tree grades correspond to the points along the d.b.h. gradient where the trees begin to lose value. Because of model fit issues, the evolution of tree value according to initial d.b.h. was modeled using a regression spline effect with the HPMIXED procedure (SAS Institute 2008).

RESULTS

Tree Value

In the first part of the conditional model, the probability of observing a sawlog varied significantly between tree grades ($P < 0.0001$, Fig. 2A), but not according to d.b.h. ($P = 0.0696$, not shown). To simplify and in the absence of a significant difference ($P = 0.9953$), we merged grades A and B. The fact that the random site effect was not significant ($P = 0.1795$) suggests that there is no major difference among the three studied sites. Grade AB trees had a probability of 83.5 percent to produce a sawlog, while the probability was down to 47.1 percent for grade C trees. As expected, a sawlog was rarely observed in D trees (below grade, 2.5 percent probability).

In the second part of the conditional model, the value of the lumber in a tree having a sawlog varied according to d.b.h. ($P < 0.0001$) and tree grade ($P < 0.0001$, Fig. 2B). Again, to simplify and in the absence of a significant difference ($P = 0.3921$), we merged grades A and B. We also merged grades C and D due to a lack of observations, as only one sawlog was observed in 26 grade D trees. The significance of the random site effect ($P < 0.0001$) suggests that an important portion of variability among the three studied sites remains unexplained.

Overall, the lumber value of a maple tree in our study varied greatly among grades (AB, C, or D) and according to d.b.h. (Fig. 2C). The highest mean lumber value reached \$109 CAD² (grade AB maple tree with a d.b.h. of 54 cm). Note that the highest overall lumber value in an individual tree (\$209 CAD) was found in a grade AB with a d.b.h. of 48 cm, while some trees with a similar d.b.h. and grade yielded no sawlog once felled, because internal decay was present and more prevalent than what was expected from assessing the standing tree.

Tree Value Change Over Time

The value of grade AB sugar maple trees with the highest mean lumber value (\$55 to 61 CAD) decreased over time independently of their risk class (Table 2, -0.8 to -5.0 percent/year). However, those with a d.b.h. of 34 cm in the CR risk class gained slightly in lumber value over a 10-year growth period (Fig. 3; 0.4 percent/year). On average, grade C trees had a low lumber value (\$10 to 13 CAD), and M trees of this grade lost lumber value over time (-3.0 percent/year). However, grade C maple trees in the lowest risk class (CR) generally increased their lumber value (4.4 percent/year), reaching a peak of 8.2 percent/year at a d.b.h. of 32 cm (Fig. 3). This size represents the d.b.h. threshold for grade C trees, which can reach grade B at a d.b.h. of 34 cm. For grade D trees, the increase in mean annual percent change in lumber value was great (27.8 to 82.6 percent/year), but had little impact overall, given the low value of these trees for lumber ($< \$1$ CAD).

² Canadian dollars

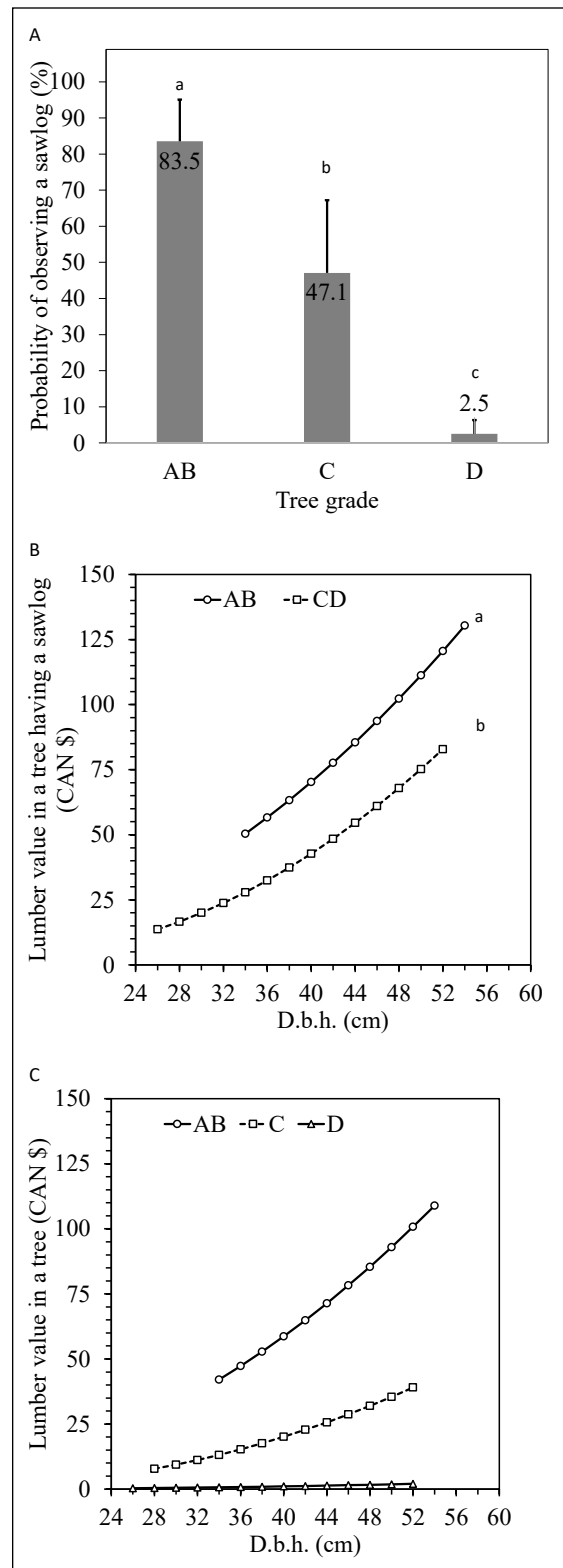


Figure 2.— Conditional model used to estimate the average lumber value of a maple tree for a given diameter at breast height (d.b.h.) and tree grade. (A) Part 1: Probability of observing a sawlog; (B) Part 2: Mean lumber value in a tree having a sawlog; (C) Conditional mean lumber value in a tree (probability $\times$ mean value in the presence of a sawlog). 1 cm = 0.4 inches. Currency conversion: \$1 CAD = \$0.82 US as of May 6, 2021.

Table 2.— Number of maple trees for which evolution was monitored, mean lumber value within a tree and mean annual percent change according to risk class and tree grade. Grades AB, C, and D are similar to U.S. grades 1 and 2, 3, and below-grade, respectively. Currency conversion: \$1 CAD = \$0.82 US as of May 6, 2021.

Risk class	Tree grade	Number of trees	Mean lumber value (\$ CAD)	Mean annual change (%)
M (moribund)	AB	24	61.13	-5.0
	C	203	12.56	-3.0
	D	213	0.68	27.8
S (surviving)	AB	30	60.25	-3.0
	C	189	12.45	0.7
	D	85	0.57	63.8
CR (conserve or reserve)	AB	214	55.08	-0.8
	C	940	9.69	4.4
	D	102	0.52	82.6
All		2,000		

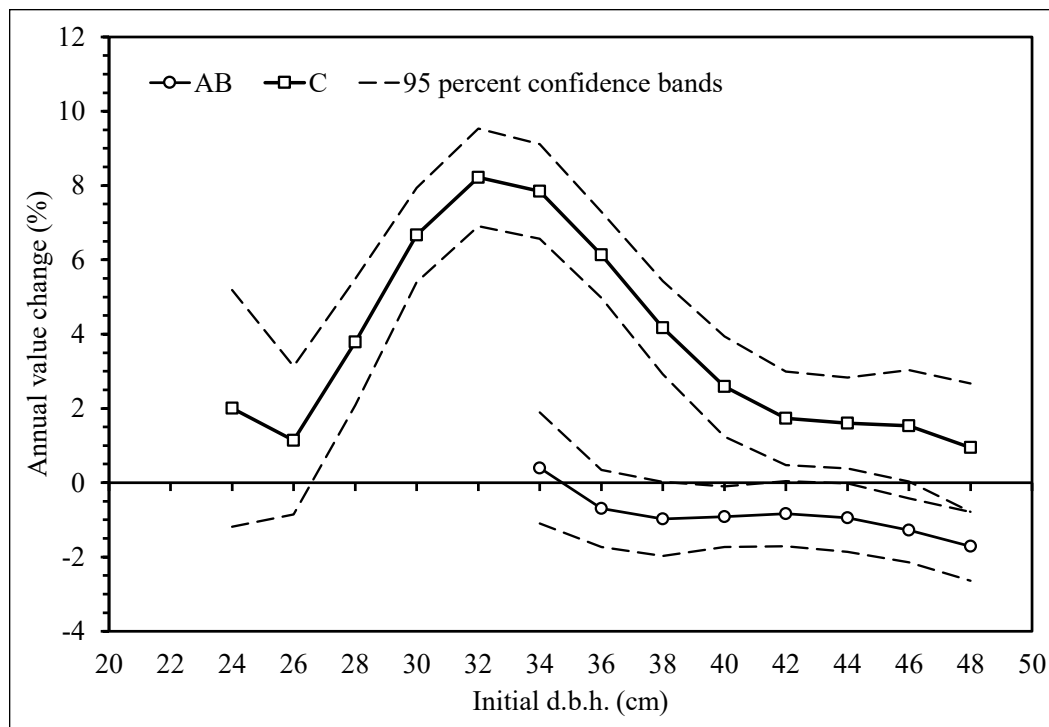


Figure 3.— Mean annual percent change in lumber value according to the initial diameter at breast height (d.b.h.) and tree grade (AB or C) for maple trees with the lowest risk class (CR, i.e., conserve or reserve). 1 cm = 0.4 inches.

DISCUSSION

Our results indicate that at the northern edge of sugar maple's distribution range, the most vigorous and high quality trees (i.e., those of the CR-AB class) reach financial maturity for a sawmill at a d.b.h. of 36 cm (Fig. 3). Larger trees lose their lumber value due to tree mortality or wood degradation, mainly through the development of decay or stem cracks (Burton et al. 2008). This result is not surprising, since vigorous and high quality trees are relatively rare on northern sites. In fact, only about 15 to 33 percent of sugar maples with a d.b.h. of 34 cm or more were graded as AB in this territory; further south, the average abundance of such trees could reach 60 percent (Guillemette and Bédard 2019). In Quebec's sugar maple bioclimatic domains (all located south of the balsam fir–yellow birch bioclimatic domain studied here), Guillemette (2016) reported d.b.h. values of 43 to 45 cm at financial maturity, depending on the region. These were similar to values suggested by Leak et al. (1987) across the states of New England and New York (i.e., 40 to 50 cm, depending on tree grade potential). Hansen and Nyland (1987) also reported a similar d.b.h. range in the state of New York. In our study, loss of value was also observed at any d.b.h. in other high quality trees (grade AB) belonging to the higher risk classes (M or S) (Table 3).

The value of vigorous maples in the lowest grade to possess a potential sawlog (grade C) increased up to a d.b.h. of almost 50 cm (Fig. 3). However, our data sampling was insufficient to provide a more precise estimate of the evolution of lumber value near this size. In the region studied, maple trees were rarer in these large d.b.h. classes, and most of them were in the higher risk classes (M or S).

In any event, despite some value gain in certain grade C maples, the value of these trees was quite low when considering sawmill profitability (Fig. 2C). A regional reference is the value of a net cubic meter of round wood. In this study, a maple tree with a d.b.h. of 46 cm yielded 1 m³ of net round wood, on average, and grade C trees in the 34 to 48 cm d.b.h. range had a mean lumber value of \$29/m³ CAD. Meanwhile, we estimate that supplying a hardwood sawmill from partial cuttings costs \$68/m³ CAD (without stumpage fees), according to a cost survey (Groupe DDM 2020). Given these values, the revenues from sawdust, chips, bark, and pulp logs need to be relatively high to offset supplying costs. In contrast, the mean lumber revenue from grade AB maple trees was \$75/m³ CAD, which is more realistic when aiming for sawmill profitability.

The main explanation for the low lumber value of grade C sugar maple trees harvested so far north is that only 47.1 percent of them produced a sawlog (Fig. 2A). For comparison, Fortin et al. (2009) observed the presence of a sawlog in 85 percent of the grade C maple trees in Quebec's sugar maple bioclimatic domains, a percentage similar to that of grade AB trees in both studies. Another reason for such a low lumber value comes from the dark coloration often present at the center of the maple trees. This “dark heart” is a serious concern because sugar maple wood is valued for its white “sap” color (Germain et al. 2015; Table 1). In the three sampled sites, the dark heart in the sawlogs covered 60 percent of the logs' diameter at the small end, on average, while in southern parts of the province, it usually ranges from 40 to 50 percent (Guillemette et al. 2021). In the 10 sites studied by Germain et al. (2015) in New York, this proportion ranged from 12 to 42 percent for trees graded 1 or 2 (the equivalent of grades A and B in our study, respectively).

A different source of lumber prices (e.g., HMR 2021³) would have led to a different evaluation of lumber revenues. However, this would have little impact on how this value evolves, and thus, on our evaluation of diameter at financial maturity. Indeed, Guillemette (2016) evaluated the effect of different sets of prices on the assessment of financial maturity size for yellow birch and concluded

³ [HMR] Hardwood market report. 2021. <https://hmr.com/> (accessed May 10, 2021).

that they yielded similar results. This could be explained by the fact that tree value evolution is mostly determined by mortality (which causes a very large loss of value), degradation of a surviving tree (moderate loss of value), and increase in diameter for surviving trees (small gain in value).

Management Implications

In our study, sugar maples located at the northern edge of the species' distribution range produced low-value lumber with little potential for improvement over time. As a result, the diameter at financial maturity of the best trees (grade AB in the risk class CR) for lumber production is small (36 cm). Consequently, for these maple stands, it is challenging to suggest appropriate silvicultural approach, and clearcutting should be considered. However, this scenario yields large volumes of pulpwood, and the absence of a large-enough pulpwood market in these northern areas reduces profitability. Thus, high-grading through a partial cut remains tempting, despite the well known problems associated with high-grading and diameter-limit cutting (see Kenefic and Nyland 2006). The main silvicultural challenge in these sites is to find a balance between harvesting the small amount of high value maple trees while keeping an acceptable growing stock, maintaining proper conditions for regeneration, and allowing enough time for forest stands to accumulate enough AB trees with a d.b.h. greater than 34 cm. The enhancement of the other functions of the forest, e.g., the nonmonetary values that these sugar maple stands might provide, would be an avenue to be further explored. Other ongoing research projects could provide a clearer view of potential solutions. However, we do not anticipate great potential for sugar maple lumber production in the study area for several decades, even if global warming improves growth conditions (Jain et al. 2021). The integration of these less profitable maple stands with the harvesting of adjacent more profitable stands is also an opportunity to consider.

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FOREST ECOLOGY AND ECOSYSTEM IMPACTS OF FORESTS

Assessing Soil Compaction Following a Winter Harvest of Northern Hardwoods

Matthew C. Kelly, Rafia Rahman, and Alexander C. Helman¹

Abstract.—Harvesting during winter is encouraged as a best management practice to protect soils during logging operations. We assessed the effects of machine traffic and slash volume on soil bulk density following a winter harvest of a northern hardwood forest on unfrozen cobbly silt loam soils. Soil samples were extracted from areas representing four levels of machine traffic (i.e., high, medium, low, and none) and two levels of overstory treatment (i.e., clearcut and partial cut). Results indicate that even low levels of traffic increased bulk density at the 0–5 cm depth. However, at the 5–10 cm depth, increases in bulk density were detected only in high traffic areas (i.e., >7 passes). No significant effects of slash volume on bulk density were detected. The mitigating effects of snow depth require further research.

INTRODUCTION

Mechanized harvest systems provide increased productivity and safety relative to manual harvesting (Cambi et al. 2015) and are widely used in the Lake States region (Gc et al. 2020). However, high ground pressures exerted by modern logging machines can impact soils (McDonald et al. 1995, McNabb et al. 2001) by altering soil structure and decreasing porosity, resulting in reduced saturated hydraulic conductivity (Jansson and Johansson 1998, McFero Grace et al. 2006), and possibly restricted root growth (Kozlowski 1999, Meyer et al. 2014).

Winter harvesting is generally encouraged to protect sensitive soils (Smith and Wass 1976, Krag et al. 1986). Ideally, winter harvests would occur over frozen ground to take advantage of the increased shear strength. However, in regions that experience early and persistent snowfall, soils remain unfrozen due to the insulating effects of the snowpack. Such is the case in Michigan's Upper Peninsula, where harvesting of northern hardwoods stands during winter is common.

The aim of this study is to assess the impacts of a mechanized winter harvest of northern hardwoods on soil bulk density in the Western Upper Peninsula. The harvest was part of the Northern Hardwood Silvicultural Experiment to Enhance Diversity (NH-SEED), and featured multiple overstory treatments, including clearcut, shelterwood, and single-tree selection (Hupperts et al. 2020).

METHODS

Harvesting occurred during February and March of 2017 within the NH-SEED study area, located at Michigan Tech University's Ford Research Forest in Baraga County, MI. The site consisted mainly of the Champion soil series, which are characterized by cobbly silt loam soils. The harvest area was dominated by sugar maple (*Acer saccharum* Marsh) and featured mild to moderate

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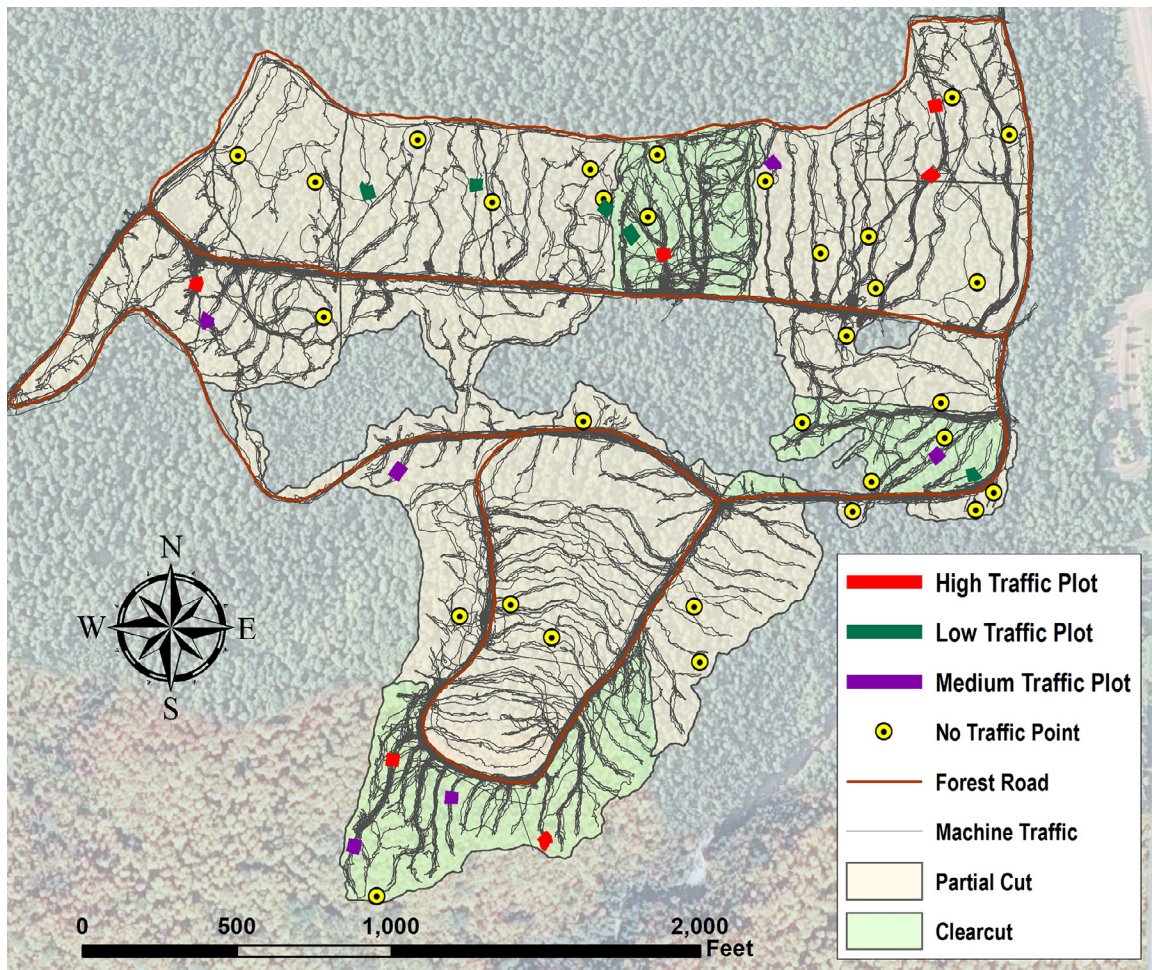


Figure 1.—Showing all skid trails and the different levels of machine traffic, where low represents 1–3 machine passes, medium represents 4–7 machine passes, and high represents areas that experienced 8 or more machine passes. Each level of machine traffic was sampled across six plots, while 31 random samples were collected in no-traffic areas.

slopes. The harvest was cut by two cut-to-length systems (i.e., harvester and processor; see Rahman 2019 for equipment information).

Each machine was affixed with a Garmin Alpha 100 or T15 receiver. Global positioning system (GPS) waypoints were collected every 3 seconds throughout the harvest. These data were analyzed in ArcMap (Esri, Redlands, CA) to identify skid trails of varying traffic intensities according to number of machine passes. Skid trails were divided into 12-meter segments (i.e., plots), and classified as low traffic (i.e., 1–3 passes), medium traffic (i.e., 4–7 passes), and high traffic (i.e., >7 passes).

Three replicated plots were randomly selected for each unique combination of traffic intensity (i.e., 3 levels) and overstory treatment (i.e., two levels), resulting in a total of 18 plots (Fig. 1). Stratifying by overstory treatment—clearcut and partial cut—was done to account for differences in slash volumes placed on the skid trail by harvester operators to protect soils. Within each plot, 12 sample points were located 2 meters apart along each side of the skid trail within the tire tracks. An additional 31 random “no-traffic” sample points were identified in ArcMap.

Soil samples were extracted using an AMS (Art's Manufacturing and Supply, American Falls, ID) soil core sampler (aka slide hammer) and a 20 cm × 5 cm cylinder. Each sample was divided into three depths (i.e., 0–5 cm, 5–10 cm, 10–20 cm), and then dried and weighed to determine bulk density. Rock fragments greater than 2 mm were separated and weighed to determine percent rock content.

Snow depth within plots could not be measured during the harvest because plots were identified post-harvest using GPS data. Thus, the effect of snow depth was not included in this analysis. However, for context, the average daily snow depth in the general area during the harvest operation was approximately 11 inches, with a maximum of 19 inches, according to data acquired from a weather monitoring station located 1 mile from the harvest site and at similar elevation.

Slash volume (m^3/m^2) was estimated at each sample point by estimating the packing ratio of woody debris within a square meter quadrat. A field guide containing examples of known packing ratios was developed in advance to assist. The field guide included packing ratios for a range of representative sample points along with photos. The packing ratios in the field guide were determined by extracting and weighing slash from within a quadrat using hand saws and a luggage scale, and then converting weight to volume using a conversion factor of $706.5 \text{ kg}/\text{m}^3$, which represents the wood density of sugar maple at 23 percent moisture content (Simpson and TenWolde 1999). The height of each field guide plot was measured from the ground to the top of the highest piece of debris in the plot to determine a three-dimensional space above the point. Thus, the packing ratio represents the percent volume of wood relative to the volume of the three-dimensional space.

SAS version 9.4 (Cary, NC) was used to analyze the data. A mixed-effects model was used within a complete random design with subsampling, with machine traffic included as a fixed-effect variable, slash volume as a random-effect variable, and bulk density as the dependent variable. The unit of analysis was the plot, which included six replications for each level of machine traffic and 31 independent samples from no-traffic areas.

RESULTS AND DISCUSSION

Traffic level was a significant factor affecting soil bulk density within the 0–5 cm layer (F-value = 5.06, P-value < 0.021), 5–10 cm layer (F-value = 2.43, P-value = 0.0659). Significant differences in bulk density were detected between no-traffic areas and all other traffic levels for the 0–5 cm depth (Fig 2). However, in the 5–10 cm layer, only high levels of traffic areas (i.e., >7 passes) had significantly higher bulk density than no-traffic areas.

These results are like previous studies that report effects of machine traffic on increased soil compaction. Jourgholami et al. (2014) observed some changes in bulk density and total porosity after fewer than 5 passes, but significant increases in penetration resistance occurred after 10 passes. Jansson and Johansson (1998) found that bulk density increased with increasing traffic (i.e., 4–8 passes) for wheeled machines and a tracked machine.

The amount of slash placed on skid trails in clearcut treatments was greater than in partial cut treatments. However, this difference was not statistically significant. Also, according to the mixed-effects model, slash volume had no significant effect on bulk density. This result may be a residue of the large number of sample points with no slash, resulting in a zero-inflated probability distribution. Further analysis may be needed to address the effects of slash.

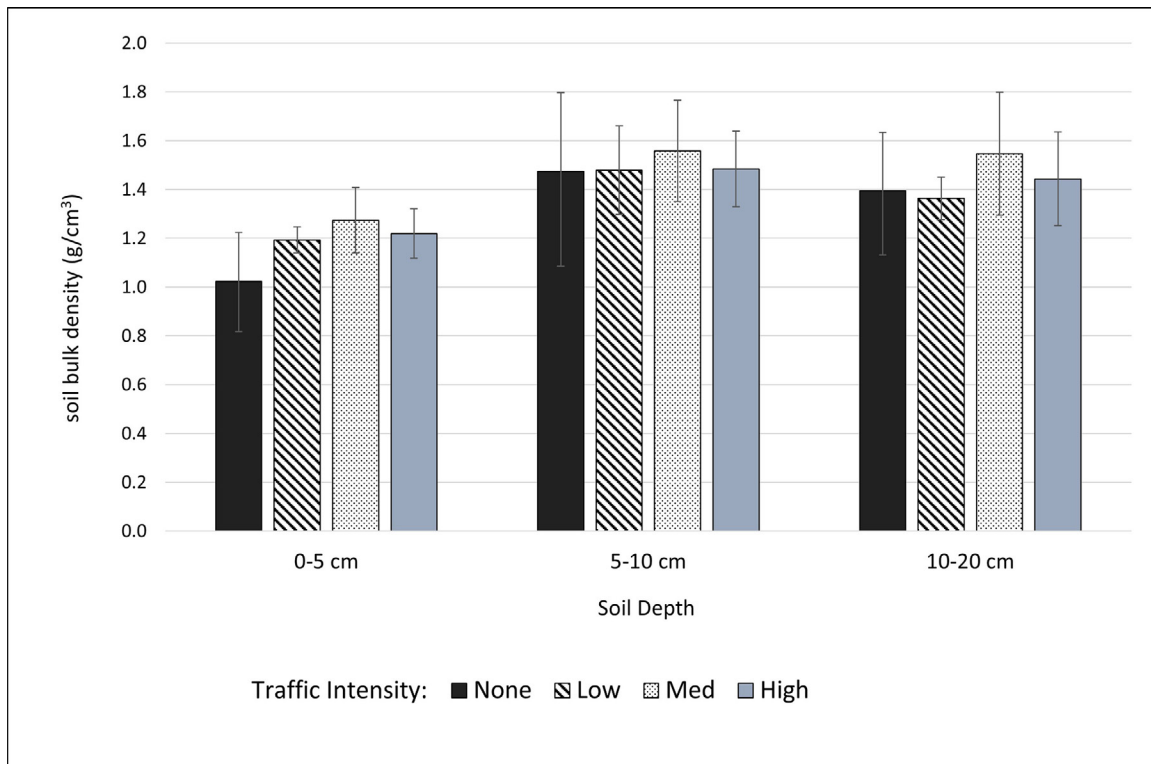


Figure 2.—Mean soil bulk density for four levels of machine traffic at three soil depths, where low represents 1–3 machine passes, medium represents 4–7 machine passes, and high represents areas that experienced 8 or more machine passes. Differing letters indicate significant difference in mean bulk density between traffic levels at $\alpha = 0.05$ level.

Previous research on the mitigating effects of slash on soil compaction are somewhat mixed. McDonald and Seixas (1997) found that slash provided some protection against compaction from a forwarder after two or more passes on loamy sand soils. In contrast, Han et al. (2006) reported no significant effects of slash when operating a cut-to-length system on fine loamy soils, though the authors noted that slash placed over skid trails can help reduce rutting.

CONCLUSION

Winter harvesting over unfrozen soils under snowpack can result in increased soil bulk density with increasing machine traffic. Thus, loggers and foresters must be attentive to soil conditions and potential impacts, even during winter harvests when soils are not frozen. While placement of logging slash on skid trails did not have a significant mitigating effect in this study, this practice is nevertheless recommended given past findings that placing slash on skid trails can effectively protect soils from rutting and compaction. A more controlled approach to studying the effects of snow depth during harvest operations would improve future research. Overall, the highest mean bulk densities reported here are just approaching levels that could restrict plant growth for silt loam soils (Daddow and Warrington 1983). Thus, the impacts of this winter harvest on future plant and tree growth might be minimal. Future research is needed to measure tree growth across plots to determine if areas with greater soil in soil bulk densities due to increased machine traffic have lasting effects on tree growth.

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Midterm Response of Understory Plant Communities after Different Regeneration Treatments in Temperate Hardwood Forests of Quebec, Canada

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Abstract.—Short-term effects of disturbances intensity on understory plant communities are well documented, however, only few studies have examined longer term effects. While increased intensity of soil and canopy disturbances tend to increase species richness in the short term due to early seral-species establishment, those competitive-pioneer species emerging from early stages of succession can become recalcitrant, which can alter patterns of natural regeneration especially by being detrimental to rarer species and such functional groups associated with closed forest habitats. We measured taxonomic and functional diversity indices and soil properties using four levels of disturbance intensity in six temperate hardwood forests of Quebec distributed along a longitudinal gradient. Reference forests—i.e., control forests with no silvicultural treatment known for ≥ 80 years (control: CON, $n=21$)—were compared to 20-year-old single-tree selection cuts (SIN, $n=13$), 20-year-old group-selection cuts (GRP, $n=15$), and 20-year-old group-selection cuts with soil scarification (GRPS, $n=17$). Species richness in group-selection treatments was higher than that in reference forests. Plant equitability and beta diversity among sites in GRP and GRPS were lower than in SIN and CON forests. More intense treatments (i.e., GRP and GRPS) contributed to the midterm persistence of early-successional competitor species (i.e., *Rubus idaeus*, *Prunus pensylvanica*) whereas sensitive species (e.g., *Monotropa uniflora*, *Dryopteris spinulosa*) occurred less often in stands with soil scarification. Of the 20-year-old treatments studied, single-tree selection cutting appears to be the most appropriate silvicultural treatment for maintaining heterogeneous understory plant communities with compositions and structures like natural forests—while more intense treatments maintain and expand for at least 20 years—species that are better adapted to a wider range of environmental conditions, including open environments.

INTRODUCTION

Within temperate forest ecosystems, the diversity of understory plant communities is a key determinant of forest dynamics. These communities play important roles in the occurrence and maintenance of several key ecological processes (e.g., nutrient recycling, regeneration; Gracia et al. 2007, Moisan-De Serres et al. 2018). Yet, these communities exhibit increased environmental sensitivity that could be exacerbated by repeated harvesting pressures that disturb the soil and forest cover (Ellum 2009, Roberts and Zhu 2002). Since the 1990s, researchers have been interested in relationships between the intensity of forest management (Foley et al. 2005), forest productivity, and biodiversity (Brockerhoff et al. 2008, Gilliam and Roberts 1995, Paquette and Messier 2010). To date, the relationships among understory plant communities' diversity, soil properties, and

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the intensity of canopy and soil disturbances remain unclear. In fact, different levels of soil and canopy disturbance intensity—relative to the size of canopy openings and the nature of machinery that is used—can have contrasting effects on biotic and abiotic conditions (Duguid and Ashton 2013, Siemion et al. 2011), therefore modifying plant community composition and soil properties (Roberts 2004). In the short term, hardwood forests that are disturbed by logging tend to have higher species richness than unmanaged forests but exhibit a lower degree of heterogeneity (Falk et al. 2008, Markgraf et al. 2020).

This response is particularly due to the establishment of competitive pioneer species that specialize in openings within communities that are composed primarily of species that are associated with late-successional forests (Archambault et al. 1998, Moola and Vasseur 2008, Naaf and Wulf 2007). During ecological succession, the coexistence of pioneer and late-successional species is generally considered to be transient, i.e., lasting less than 20 years (Moola and Vasseur 2008). However, for a given disturbance, the functional traits of competitive pioneer species and their spatio-temporal capacities to exploit available resources may allow them to remain in the community longer and, ultimately, slow down successional trajectories (Roxburgh et al. 2004, Wyatt and Silman 2010). In recent decades, management of North American hardwood forests has evolved toward alternative regeneration processes that aim to maintain some type of continuous canopy cover (Seymour et al. 2002), multi-aged stands to maintain forest resilience to global change and better integrate biodiversity conservation objectives (Messier et al. 2015).

For instance, harvest practices that promote permanent forest cover and uneven-aged structure have negligible negative impacts on abiotic conditions and vegetation diversity (Raymond et al. 2018), allowing the natural dynamics of regeneration to be maintained. The mid-lasting effects of harvesting intensity on soil properties and understory vegetation over approximately 20 to 30 years have not been assessed in a well documented manner in temperate deciduous forest of northeastern America. Thus, it is important to verify whether regeneration treatments that stay at the margin of the range of natural canopy gaps (i.e., group-selection cuts; Seymour et al. 2002) contribute to longer persistence of these competitive species and to the decrease in structural and functional heterogeneity of understory plant communities, or whether they allow a convergence of plant communities toward the attributes of unmanaged forests (Duguid and Ashton 2013, Paillet et al. 2010).

METHODS

We compared key soil chemical properties and diversity of understory plant communities along a gradient of canopy opening and soil disturbance in six deciduous forests located in the yellow birch-sugar maple bioclimatic domain (Saucier et al. 2009) in Quebec, Canada. The sites were selected with the aim of comparing reference forests (i.e., control forests that were not logged for at least 80 years (CON, $n = 21$) to three regeneration treatments, applied once about 20 years ago and representing a gradient of canopy and soil disturbance intensity). These are: (1) single-tree selection cuts (SIN, $n = 13$), an uneven-aged low-intensity treatment removing about 30 percent of average basal area; (2) group-selection cuts (GRP, $n = 15$), an uneven-aged moderate-intensity treatment alternative to clearcuts and resulting in openings ranging in area from 1500 m² to 2500 m²; (3) group-selection cuts with soil scarification (GRPS, $n = 17$), an uneven-aged moderate-intensity alternative treatment with the additional purpose of creating soil microsites for some commercial tree species such as yellow birch.

Each site consisted of 3 to 5 randomized complete blocks in which regeneration treatments were compared. Blocks and sites were used as random variables in our linear-mixed model analyses. Within each sampling unit, chemical properties of forest floor and surface mineral soil (i.e., pH,

total C and N, extractable P, and exchangeable basic cations) and different understory plant diversity indices (i.e., species richness, evenness index, and functional dispersion) were assessed about 20 years after the application of the treatments. To compare functional redundancy between the treatments, we determined the community weighted means (CWM) for three environmental performance traits (sensu Violle et al. 2007); namely (1) biological type, (2) reproductive mode, and (3) shade tolerance. These traits were selected for the analyses because of their links with competitive abilities (i.e., biological type) and potential for colonization following disturbance (i.e., shade tolerance and reproduction mode). Finally, to assess the conservation potential of the different regeneration treatments, we also tested the responses of species identified in the literature as potentially sensitive (Haeussler et al. 2002, Moola and Vasseur 2008) and potentially recalcitrant (Bell et al. 2011, Royo and Carson 2006).

RESULTS AND DISCUSSION

First, the geographic location of sites explained a much more substantial proportion of the variation of soil properties than regeneration treatments. The regeneration treatments considered in our study had more limited, longer-term effects on soil properties than we had anticipated, although other studies have shown medium-term recovery of soil chemical properties following forest harvesting and soil scarification treatments (Hope 2007). However, our results indicate group-selection cuts with a soil scarification treatment in temperate hardwood forests can leave a legacy effect on soils that persists in the medium term, especially in the surface horizon. Twenty years after the application of group-selection cuts and soil scarification, FH-horizon thickness in CON was significantly higher (i.e., almost twofold) than in the GRPS. C:N ratio of the organic horizon in the control stands were higher than in the GRPS. The decrease of FH-horizon thickness and C:N ratio in the group-selection cuts can be attributed to the extraction of forest biomass and subsequently lower inputs of fresh litter (Clarke et al. 2015, Saint-Laurent et al. 2000, Thiffault et al. 2011), higher litter decomposition rates from early-successional species compared to late-stage species (Kazakou et al. 2009), and the burial of surface organic matter in the soil-mineral horizon (Henneb et al. 2019). Concurrently, species richness and composition differed weakly among canopy opening treatments, being almost similar between the SIN and the CON forests (Fig. 1). These results are consistent with other studies that have measured negligible effects of single-tree selection cuts on environmental conditions and understory-plant communities' diversity (Raymond et al. 2018, Smith et al. 2008). Twenty years after the application of the regeneration treatments, species richness was slightly higher and species-equitability index was lower in the group-selection cuts due to the presence of a greater number of species that are associated with open habitats (Table 1; Deconchat and Balent 2001, Hilmers et al. 2018). When considering species abundance or community-weighted means of functional groups, our results showed that increasing the intensity of disturbance tended to favor biotic-homogenization processes (Brewer et al. 2012, Falk et al. 2008, Markgraf et al. 2020). Although control forests and SINs in our study had fewer understory species on average, they were associated with higher beta diversity between sites compared to GRPS, indicating more heterogeneous plant communities across study sites. Our study suggests increasing canopy-opening intensity may increase the potential for the installation of colonizer and "recalcitrant" species that are present in the medium term (Royo and Carson 2006), such as *Rubus idaeus* and *Prunus pensylvanica* (Table 2), while being detrimental to rarer species and such functional groups associated with closed forest habitats.

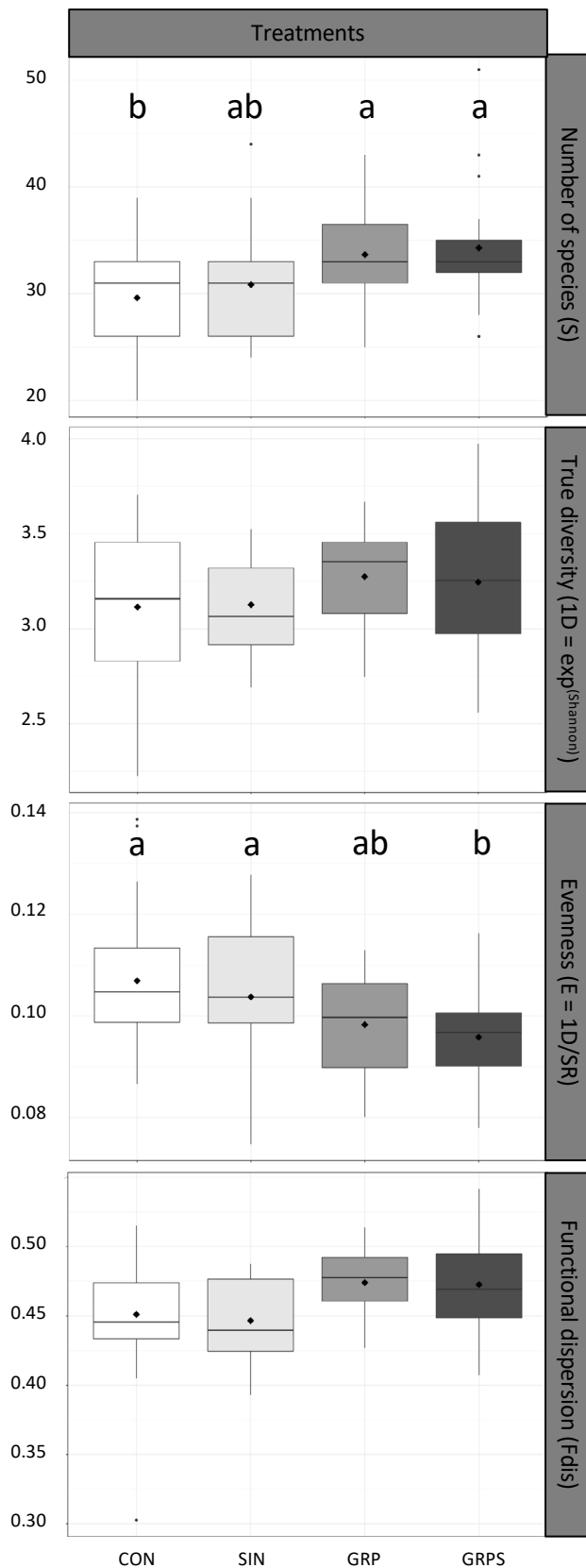


Figure 1.—Species richness (S), true diversity ($1D$), evenness index (E), and functional dispersion index ($Fdis$) of understory plant communities in southern Quebec, as a function of regeneration treatments. Means with different letters significantly differ following pairwise Tukey's tests ($P < 0.05$). Box-and-whisker plots in each panel display 25th and 75th percentiles (the inter-quartile range from the lower and upper edges of the box), the horizontal lines within boxes indicate the 50th percentiles (i.e., medians), and bullets within boxes indicate means; whiskers below and above boxes indicate 10th and 90th percentiles, respectively, beyond which dots indicate outliers (i.e., values $> 1.5 \times IQR$).

Legend:

CON: controls

SIN: single-tree selection cut

GRP: group-selection cut

GRPS: group-selection cut with scarification

Table 1.—Functional diversity (Rao index), mean species richness (S), and mean relative occurrence (F) of environmental performance traits as a function of regeneration treatments

Biological type	Index	CON	SIN	GRP	GRPS
Functional diversity	Rao	0.40	0.41	0.41	0.42
Evergreen	S	1.7 (1.0)	1.5 (1.1)	1.4 (0.9)	1.3 (1.3)
	F	0.34 (0.25)	0.31 (0.22)	0.28 (0.30)	0.27 (0.32)
Deciduous	S	3.2 (0.8)	3.2 (0.9)	3.8 (0.9)	3.5 (1.3)
	F	0.46 (0.33)	0.46 (0.45)	0.54 (0.33)	0.50 (0.33)
Shrubs	S	5.2 (1.7)	4.3 (1.4)	5.7 (1.9)	6.0 (1.9)
	F	0.43 (0.27)	0.36 (0.25)	0.48 (0.29)	0.50 (0.28)
Bushes	S	1.3 (0.9) b	1.8 (0.9) b	1.7 (1.0) b	2.1 (0.9) a
	F	0.33 (0.23) b	0.44 (0.29) b	0.43 (0.5) b	0.53 (0.28) a
Asterales	S	1.3 (0.9)	1.1 (1.1)	1.6 (1.1)	1.1 (0.8)
	F	0.32 (0.25)	0.27 (0.18)	0.40 (0.26)	0.28 (0.22)
Graminaceae	S	0.9 (0.8) b	0.8 (0.8) b	1.3 (0.6) b	1.6 (0.6) a
	F	0.45 (0.24) b	0.42 (0.16) b	0.63 (0.42) a	0.79 (0.12) a
Monocots	S	4.5 (1.6)	4.2 (1.6)	4.3 (1.7)	4.9 (1.6)
	F	0.50 (0.27)	0.54 (0.26)	0.48 (0.26)	0.55 (0.34)
Sporophytes	S	4.1 (1.6)	3.4 (1.5)	4.5 (1.6)	4.9 (1.6)
	F	0.37 (0.28)	0.32 (0.26)	0.41 (0.27)	0.45 (0.27)
Other flowering plants	S	5.5 (2.9)	6.6 (2.1)	6.2 (2.0)	6.3 (1.9)
	F	0.26 (0.25)	0.32 (0.25)	0.30 (0.25)	0.30 (0.28)
Reproductive mode					
Functional diversity	Rao	0.33	0.34	0.34	0.33
Vegetative	S	14.3 (4.1) b	15.3 (2.9) b	15.4 (3.2) b	16.6 (2.0) a
	F	0.36 (0.27)	0.38 (0.28)	0.39 (0.29)	0.41 (0.33)
Sexual & vegetative	S	10.0 (2.2) ab	9.3 (2.4) b	11.8 (2.6) a	12.7 (3.5) a
	F	0.41 (0.28)	0.38 (0.29)	0.47 (0.26)	0.48 (0.25)
Sexual	S	2.5 (0.7)	2.2 (1.3)	2.6 (1.0)	2.7 (1.1)
	F	0.31 (0.18)	0.27 (0.15)	0.33 (0.25)	0.32 (0.29)
Shade tolerance					
Functional diversity	Rao	0.30	0.28	0.32	0.32
Shade intolerant	S	1.0 (1.3) b	0.6 (0.9) b	2.0 (1.1) a	2.5 (1.3) a
	F	0.15 (0.09) ab	0.09 (0.09) b	0.29 (0.18) ab	0.35 (0.20) a
Intermediate tolerance	S	6.9 (1.9)	6.9 (2.6)	7.5 (2.2)	8.1 (2.0)
	F	0.34 (0.25)	0.34 (0.26)	0.37 (0.27)	0.41 (0.27)
Shade tolerant	S	19.8 (5.3)	20.2 (4.6)	21.1 (4.9)	21.2 (3.1)
	F	0.41 (0.27)	0.42 (0.27)	0.44 (0.29)	0.44 (0.32)

Values in parentheses are standard deviations of the means. Within rows, means followed by the same letter do not differ significantly at $\alpha = 0.05$ according to pairwise Tukey's tests. CON: control; SIN: single-tree selection cut; GRP: group-selection cut; GRPS: group-selection cut with scarification.

Table 2.—Taxon-specific responses of potentially sensitive and potentially recalcitrant species to regeneration treatments

		Relative Occurrence				ANOVA
		CON	SIN	GRP	GRPS	p-value
Sensitive						
	<i>Athyrium filix-femina</i>	1.12	0.55	1.11	1.27	0.7947
	<i>Circeae alpina</i>	0.37	0.23	0.26	0.06	0.7173
	<i>Coptis trifolia</i>	4.96	6.52	3.69	2.65	0.5869
	<i>Cypripedium acaule</i>	0.64	0.70	0.59	0.18	0.6244
	<i>Dryopteris spinulosa</i>	31.46 a	27.94 a	26.28 a	11.03 b	0.0154
	<i>Lycopodium</i> spp.	1.97	1.20	1.66	1.09	0.8245
	<i>Monotropa uniflora</i>	0.42 a	0.47 a	0.58 a	0.13 b	0.0016
	<i>Oxalis acetosella</i> ssp. <i>montana</i>	15.40	9.61	11.79	6.01	0.0849
Recalcitrant						
	<i>Acer spicatum</i>	25.41	29.27	27.51	21.15	0.6159
	<i>Corylus cornuta</i>	5.52	5.32	5.14	6.71	0.9206
	<i>Populus tremuloides</i>	0.05	0.01	0.36	0.44	0.1056
	<i>Prunus pensylvanica</i>	0.04 b	0.29 b	2.24 a	3.56 a	0.0441
	<i>Pteridium aquilinum</i>	1.25	1.20	0.40	0.42	0.6335
	<i>Rubus idaeus</i>	0.41 b	0.44 b	3.52 a	2.83 a	0.0370

Mean relative occurrence values (%) are presented and two-way permutation ANOVA p-values. Significant treatment effects are represented by a *P*-value in bold ($P < 0.05$). Within rows, means followed by the same letter do not differ significantly from one another at $\alpha = 0.05$ according to pairwise Tukey's tests. CON: controls; SIN: single-tree selection cut; GRP: group-selection cut; and GRPS: group-selection cut with scarification.

CONCLUSION

Our results confirm sites' locations, and therefore their specific abiotic conditions, are responsible for much of the variation in plant communities and soil properties. Our results also suggest that, in temperate hardwood forests, there is a legacy of regeneration treatments with soil scarification on soil properties, particularly in the surface horizon. This legacy, in turn, can affect the composition and diversity of understory-plant communities. The most intense silvicultural treatments we investigated (i.e., GRP and GRPS) not only resulted in slightly increased species richness in the medium term, but also a decrease in understory plant communities' heterogeneity between sites. Indeed, these treatments contributed to a greater-relative occurrence of shade-intolerant competitive species adapted to disturbed environments and potentially recalcitrant in the longer term, which could compete with commercial species and alter plant community composition. Among the studied treatments, SIN appeared to be the most appropriate silvicultural treatment for maintaining soil functions and understory plant communities of unmanaged forests. On the other hand, more intense treatments tended to favor species adapted to a wider range of abiotic conditions, including open environments. Therefore, at the landscape level, the guarantee of maintaining the highest biodiversity of understory plant communities will lie in the search for adequate spatial representativeness of the different silvicultural treatments by considering the functions of the species that they favor over the long term.

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Emergent Properties of Deadwood in Canopy Openings: A Response of the Wood Inhabiting Fungal Community to Manipulation of Forest Structure

Lili Perreault, Jodi A. Forrester, and David J. Mladenoff¹

Wind disturbance in northern hardwood forests creates heterogeneously distributed structural attributes such as downed woody debris (DWD) across temporal and spatial scales. Wood inhabiting fungi (WIF) contribute to ecosystem carbon (C) dynamics through their role in deadwood turnover and long-term C storage. Deadwood reductions linked to forest management may alter WIF richness and composition, thus indirectly influencing the persistence of deadwood and its contribution to C and nutrient cycling. Forest structural complexity was manipulated via canopy gap creation and DWD addition that mimic natural disturbance by windfall within a deciduous northern hardwood forest (Wisconsin, United States) to examine its effect on deadwood-associated biodiversity and function. Experimental sugar maple (*Acer saccharum*) logs were resampled 10 years after placement and profiled using high throughput sequencing techniques to determine the assembly of fungal community composition and its relationship to wood decay rates. We built on previous studies at the experimental site that reported enhanced fungal abundance and richness in response to increased structural complexity (i.e., gaps plus CWD), and a negative relationship between DWD respiration and fungal richness 4 and 5 years after treatment. Canopy gap creation was more important in shaping overall fungal community composition than was DWD addition, but overall structural complexity was not a significant predictor of fungal operational taxonomic units (OTU) richness. The WIF community possibly responded to gap disturbance by favoring species able to persist under more extreme microclimates caused by gaps. The species assemblage in the DWD treatment was unique to other treatments, where consistent microclimatic conditions and the abundance of DWD substrates may have favored host specialists. Fungal-OTU richness was significantly and inversely related to DWD decay rates, likely due to competition for resources. In contrast, fungal-OTU composition was not significantly related to DWD decay rates, canopy openness or DWD-addition amounts. Our study site represents a diverse fungal community in which complex interactions among wood inhabiting organisms and abiotic factors are likely to slow DWD decomposition, indicating an opportunity to enhance C storage capacity within northern hardwood forests by maintaining a biodiverse and microsite-rich ecosystem.

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Clearcuts Drive Dissimilar Small Mammal Assemblages in Northern Hardwood Forests

Jared D. Wolfe, Breanna R. Gusick, Kristin E. Brzeski, and Yvette L. Dickinson¹

Composition and diversity of small mammal communities are sensitive to bottom-up effects where variation in vegetative structure, climate, and microclimates affect the food resources upon which small mammals depend (Pinotti et al. 2011). Sensitivity to changes in forest structure reflect the close trophic linkages between herbivorous, granivorous, and insectivorous small mammals and the surrounding vegetation they use as food resources and cover (Niedziałkowska et al. 2010). Subsequent variation in small mammal community structure and abundance can result in cascading effects on carnivores, such as fisher (*Pekania pennanti*) and American marten (*Martes americana*), two forest dwelling carnivores valued by trappers throughout the Midwest (Buskirk and McDonald 1989). Given the role of small mammals in supporting a functional forest ecosystem, understanding how different silviculture prescriptions and subsequent changes in vegetative structure affect small mammal community assemblage is an important step toward sustainable forest management. Renowned for its forested and working landscapes, Michigan's Upper Peninsula is 72 percent forested, dominated by northern hardwood forest, with a third of the land privately owned by individuals and families. Coupled with natural disturbances (e.g., fire, winter, windthrow), the patchwork of private ownership across the Upper Peninsula of Michigan has created a heterogeneous landscape where conflicting objectives of timber extraction and maintenance of wildlife habitat affect a diversity of mammalian species. Forests in the Upper Peninsula hosts 23 species of volant and nonvolant mammals, including shrews, moles, voles, mice, rats, lemmings, chipmunks, and squirrels.

The diversity of small mammals in the Upper Peninsula represents a collection of dissimilar life history strategies and ecological guilds that support a variety of ecosystem functions. To determine how different forest management strategies affect small mammals in the Upper Peninsula, we captured small mammals across multiple experimental silvicultural treatments at the Northern Hardwood Silvicultural Experiment to Enhance Diversity (NH-SEED) experimental forest located at the Ford Center and Forest, in Michigan's Upper Peninsula. As of 2019, the NH-SEED included the following four silviculture canopy prescriptions: clearcut (n = 9 sites), single-tree selection (n = 9 sites), shelterwood-high residual (n = 18 sites), and shelterwood-low residual (n = 18 sites). Each treatment was divided into three levels of site preparation treatments, encompassing approximately 15 ha each—control (n = 18 sites), scarification (n = 18 sites), and artificial tip-up (n = 18 sites)—for a total of 54 sites. At each site, four Sherman traps (H.B. Sherman Traps, Inc., Tallahassee, FL) were deployed, in which two traps were placed in the center of the site, and two additional traps placed 25 m due north from the center of the site. Each trap was baited with peanut butter and sunflower seeds and provisioned with batting for warmth. Our goal was to determine how specific silviculture techniques increased, or diminished, small mammal richness. Additionally, we aimed to measure how silviculture techniques shifted patterns of small-mammal community structure.

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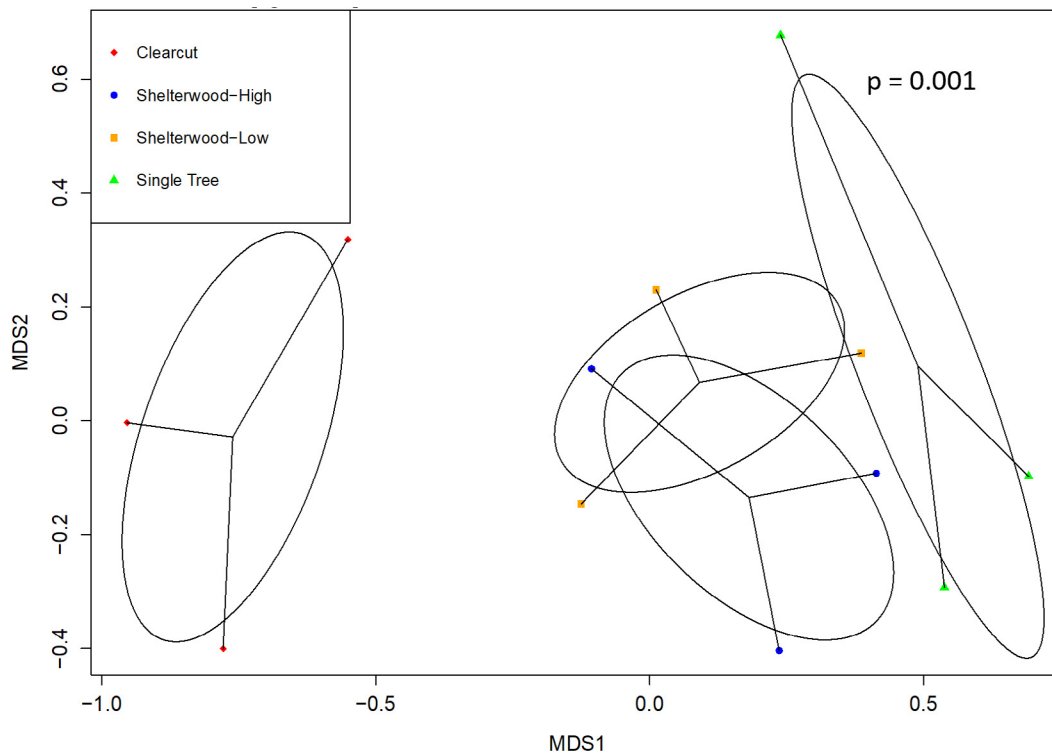


Figure 1.—NDMS ordination demonstrating differences in small mammal community structure based on 129 individual captures, representing 11 different small mammal species, in four different experimental canopy treatments at NH-SEED experimental forest, Alberta, MI.

A total of 525 animals (including 129 recaptures), representing 11 species, were captured at the NH-SEED during 1387 trap nights, between June through September of 2019. The four most captured small-mammal species were the southern red-backed vole (*Myodes gapperi*, $n = 150$), white-footed mouse (*Peromyscus leucopus*, $n = 131$), deer mouse (*Peromyscus maniculatus*, $n = 128$), and meadow-jumping mouse (*Zapus hudsonius*, $n = 38$); all of which were marked or tagged. Of the recaptured mammals, *P. leucopus* had 66 recaptures, *P. maniculatus* had 50 recaptures, *M. gapperi* had 13 recaptures, and *Z. hudsonius* had zero recaptures. Small mammal community composition was assessed across canopy and site preparations using nonmetric multidimensional scaling (NMDS) ordinations (Fig. 1). Based on a bootstrapping analysis, we found no statistically significant difference between small mammal community assemblage across site preparation treatments ($p = 0.702$); however, we did find that canopy preparation had a significant effect on community assemblage ($p = 0.001$), with clearcut and single-tree selection treatments driving variation among communities. Species richness was estimated by rarefaction and extrapolation for sample-based incidence data. Across canopy preparations, clearcut treatments had the greatest estimated number of species with $10.84 (\pm 1.46 \text{ SD})$ and single-tree selection treatments had the lowest estimated species with $7.86 (\pm 1.42 \text{ SD})$. Estimated species richness across site preparations was $11.21 (\pm 1.33 \text{ SD})$ throughout scarification treatments and $9.06 (\pm 0.70 \text{ SD})$ within tip-up treatments (Fig 2). Our results suggest that clearcuts result in species rich mammal communities that are significantly different than those treatments that maintain variable amounts of canopy cover. This probably reflects stark differences in vegetative structure and microclimate conditions that exclude some forest-obligate mammal species, while creating niche space for generalists and nonforest species. Given substantial variation in community composition across canopy treatments, maintaining a diversity of forested stands with variable amounts of canopy cover across the landscape is necessary to optimize small mammal diversity. This “diversity of diversity” forest management strategy may represent an important consideration when managing for diverse assemblages of small mammals, and the forest carnivores that depend on them.

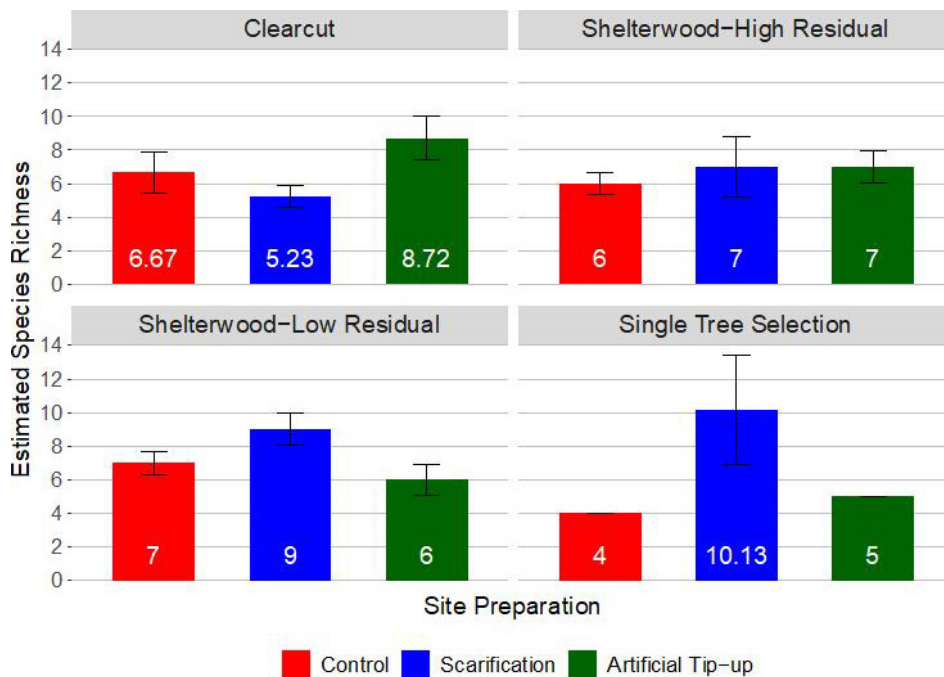


Figure 2.—Estimated species richness, based on rarefaction, of small mammal communities captured in 12 different experimental silviculture treatments at NH-SEED experimental forest, Alberta, MI.

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Novel Applications of iDNA Tool for Measuring Small Mammal Community Biodiversity via Silphid Beetles

Katherine E. Schneider, Tara L. Bal, and Kristin E. Brzeski¹

Abstract.—Environmental DNA (eDNA) and invertebrate DNA (iDNA) have become popular techniques in biodiversity surveys. Established iDNA sources to survey mammals include biting invertebrates, but *Silphidae* (carrion feeders) have yet to be reported in literature. These beetles could provide a less invasive tool to survey mammalian communities. To validate use of iDNA methods using silphids, fieldwork was conducted in Michigan Technological University's Ford Forest in the Northern Hardwood-Silviculture Experiment to Enhance Diversity (NH-SEED). Modified pitfall trapping was conducted and we successfully sequenced diet DNA from silphids, showing their potential as an iDNA tool. Additionally, trapping in NH-SEED showed a potential treatment selection by silphids in different harvesting methods and ground treatments, though no statistically significant results were determined in our preliminary data collection. Further studies are necessary to conduct more extensive sampling to determine silviculture treatment preferences and to further explore potential applications for silphids as an iDNA tool.

INTRODUCTION

Environmental DNA (eDNA) is a novel tool where DNA of plants, animals, or bacteria are extracted from environmental samples, such as soil or streams, to assay community-wide biodiversity. A subset of eDNA is invertebrate DNA (iDNA), where typically, vertebrate DNA is extracted from stomach contents of invertebrates to determine the vertebrate communities they feed upon. These sampling methods can provide an accurate representation of the vertebrate diet species composition (Andersen et al. 2012, Calvignac-Spencer et al. 2013). eDNA and iDNA samples provide information on the organisms in that environment or diet and are tools used in conservation biology without having to directly sample the target wildlife (Bohmann et al. 2013). The introduction of cutting edge genetic tools has shifted the focus from traditional trapping to these newer methods. With iDNA techniques, blood- or dung-feeding insects become a helpful tool for estimating wildlife diversity (Calvignac-Spencer et al. 2013). Methods have been developed to use dung beetles (Scarabaeidae: Coleoptera), or mosquitoes and flies (Diptera), or ticks (Ixodidae), and other blood-feeding invertebrate groups to study wildlife. Silphids (Silphidae: Coleoptera) are made up of two major subfamilies, carrion beetles (*Silphinae*) and burying beetles (*Nicrophorinae*), with carrion beetles being indiscriminate in host-carcass preference and burying beetles preferring small mammal carcasses to bury for reproduction and consumption. No research has yet focused on utilizing silphid beetles to extract small-mammal DNA for small mammal population studies. Silphids have been mentioned in reviews as a potential iDNA source, though no literature has explored the actual use of these species (Calvignac-Spencer et al. 2013).

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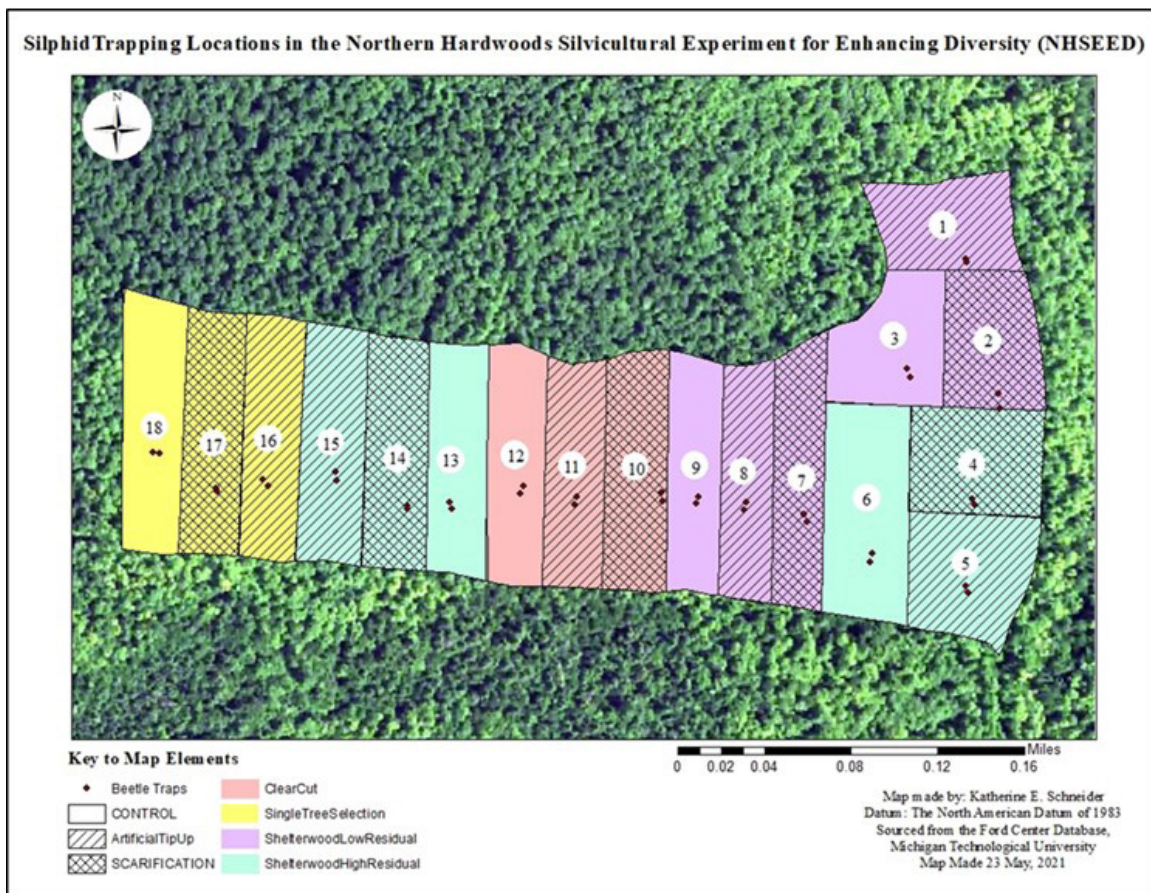


Figure 1.—Silphid trapping locations from 2019 in a portion of the Northern Hardwood Experiment to Enhance Diversity (NH-SEED) cutting trials in the Ford Forest, Alberta, MI.

Our research was focused on evaluating the utility of silphid beetles as an iDNA source, specifically looking at how useful these invertebrates may be for estimating small mammal community composition across varying silviculture practices.

PRELIMINARY FINDINGS

Silphid Beetle Trapping

To test how silphid diets and populations might be influenced by silviculture practices, pitfall traps were set in May through October 2019 in one-third (18 total) of the experimental treatment plots in the Northern Hardwoods-Silviculture Experiment to Enhance Diversity (NH-SEED) on Michigan Technological University's Ford Forest (Fig. 1). Treatment plots were a mix of clearcut, shelterwood, and selection systems with different ground-disturbance intensities (Hupperts et al. 2020). Each treatment plot had two traps installed. The pitfall traps were cups buried so that the opening was level to the soil's surface, with a lid placed loosely over them to prevent rainwater incursion and captured invertebrates from flying out; a classic method for sampling ground dwelling invertebrates (e.g., Niemälä et al. 1990). Bait was catfish bait and raw beef, with pinkie mice used in the last month of trapping. The 36 total traps were baited and monitored in six different sampling sessions over the summer lasting approximately 14 days each, checked weekly. We incorporated a sterilized two-tiered mesh layer in the trap prior to entering the field to separate the beetles from the bait, avoiding contamination as much as possible.

Traps were checked once a week after they were set and each trapped silphid beetle's exterior was swabbed in the field for a body sample and a fecal sample, then frozen for 3 weeks until a dissection was performed to remove stomach samples. For each of the sample types, DNA was extracted with a modified Qiagen (Hilden, Germany) Dneasy® blood and tissue extraction method, then diet DNA was amplified via a polymerase chain reaction (PCR) using the vertebrate primer pair 12S-V5F/R. Samples with a successful PCR, as determined by an agarose gel, were Sanger sequenced to identify the diet item. Of the 20 adult beetles sampled, five DNA sequences of mammalian diet items were successfully identified, including star-nosed mole (*Condylura cristata*), deer mouse (*Peromyscus maniculatus*), canid (*Canis spp.*), and cow (*Bos taurus*), with the cow likely due to bait contamination.

Future applications

For specific trapping locations, the average number of beetles trapped per each silvicultural treatment indicates trends for preference of ground and silviculture treatments. Previous studies have found more significant impacts of overall forest management regimes on ground dwelling beetle abundance and presence than on canopy density or tree species at sites (Werner and Raffe 2000). In our initial study here, more beetles were trapped in the single-tree selection systems that retained higher-basal areas, and in treatments with tip-ups compared to scarification. Though these are not statistically significant findings, we are continuing sampling efforts in 2021 and 2022. The preliminary data presented here paves the way for future data collection to continue with more intensive trapping and iDNA analysis throughout the full NH-SEED treatment and control area. Silphid iDNA sampling methods may be an important tool for monitoring mammals that are at risk or difficult to sample with traditional-trapping methods. Due to the importance of silphids as nutrient cyclers through their aid in the decomposition process and their beneficial role reducing fly species through carcass competition (Steele 1927), understanding their preferences for silviculture treatments can also contribute to management plans that consider a diversity of species. Additionally, use of iDNA to better understand diets can better elucidate how invertebrates, including burying beetles and others, and vertebrates, specifically small mammals, may be using different forest systems with variable silvicultural treatments. Silvicultural practices that affect silphids may be linked to a web of other organisms, leading to the development of management plans and practices that are more comprehensive regarding the biodiversity of species impacted.

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Wild, Native Pollinators Forage in Forest Canopies: Evidence of Canopy Pollen Consumption in Digestive Tracts of Forest Bees

Kass Urban-Mead, Maria van Dyke, Paige Muñoz, Anna Espinoza, Jessica Gillung, Rachel Fordyce, Scott H. McArt, and Bryan N. Danforth¹

The contiguous United States is home to over 4,000 species of native, wild bees in addition to the European honeybee (*Apis mellifera*). Although a natural area is often positively correlated with increased wild bee diversity, abundance, and species richness, forests have historically been ignored as potential bee habitat due to their dense canopy cover and dominance by wind-pollinated trees. Yet increased forest sampling has revealed higher than expected numbers of wild pollinators active in deciduous hardwood forests. Over 3 years, we deployed canopy and understory traps in second-growth woodlots and orchard-adjacent forest plots in the early spring. We found over one-fifth of New York's 417 wild bee species active in forest canopies and understories. Canopies were particularly dominated by solitary female bees whose primary activity is foraging pollen for nest provisioning. We describe the nest habits of canopy-active bees, including a focus on wood-nesting bees who may benefit from coarse woody debris in forest habitats. Finally, we dissected over 4,000 canopy- and understory-caught wild bee pollinators and identified the pollen in their digestive tracts. In addition to pollen from understory herbs, shrubs, and adjacent orchards, bee digestive tracts also held large amounts of maple (*Acer* spp.) pollen, as well as oak (*Quercus* spp.), hickory (*Carya* spp.), birch (*Betula* spp.), and ash (*Fraxinus* spp.). Pollen consumption tracked mast bloom (e.g., pollen availability) of different years, and we discuss the implications of wind-pollinated tree pollen consumption for wild bees. We explore avenues for considering ecological forest management for vibrant forest bee pollinator populations. We particularly suggest landscape scale maintenance of multiple successional stages and tree diversity across the landscape, vertical structure, and an emphasis on downed and standing deadwood as nest habitat.

UPDATE

Details of this research has been published:

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Urban-Mead, K.R.; Muñoz, P.; Gillung, J.; Espinoza, A.; Fordyce, R. [et al.] 2021. **Bees in the trees: diverse spring fauna in temperate forest edge canopies**. Forest Ecology and Management. 482: 118903. <https://doi.org/10.1016/j.foreco.2020.118903>.

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FOREST HEALTH

Beech Bark Disease Tolerance: An Emerging Concept in American Beech Management

Laura S. Kenefic, David Houston, William Livingston, Stacy McNulty, Jeanette Allogio, Bethany L. Muñoz Delgado, and Lauren Keefe¹

INTRODUCTION

Beech bark disease (BBD) affects the health and quality of American beech (*Fagus grandifolia*). This disease complex, which spread from Nova Scotia in the late 1800s to the Great Lakes region by the early 2000s, is caused by the nonnative beech scale insect *Cryptococcus fagisuga* and *Neonectria* fungi. The scale insect feeds on living bark, altering the tissue, and allowing the fungus to enter, establish, and spread. This kills the cambium, resulting in cankers and ultimately causing mortality of many trees.

The spread of BBD is classified into three stages or zones (Shigo 1972). In the advance front, the scale insect arrives and proliferates. In the killing front, high levels of the scale insect and fungus result in high levels of beech mortality, especially of larger trees. In the aftermath zone, endemic populations of the causal complex result in stands of mostly small, defective beech with some larger trees. In these areas, forest management recommendations often advise removing all beech except the very small percentage (<1 percent) with smooth bark due to resistance to scale infestation. Yet this has the potential to reduce ecological contributions of beech such as wildlife habitat provision (Cale and McNulty 2018).

An emerging concept relevant to beech management—tolerance to BBD— suggests that some trees infested by the scale insect (and therefore not resistant) may have the ability to wall off bark tissue infected by the fungi before they reach the cambium. Increases in the underlying periderm layers result in raised bark lesions (delimited cankers) that may indicate BBD tolerance (Ostrowsky and Blanchard 1983). These raised lesions differ in appearance from sunken cankers that form where fungal infection killed the cambium. The objective of this study was to evaluate beech in the aftermath zone to determine whether raised bark lesions are associated with other measures of BBD tolerance such as relatively better crown condition and growth. We hypothesized that trees with more raised bark lesions are more tolerant of BBD and thus exhibit less crown dieback and more growth.

METHODS

This research was conducted on the Penobscot Experimental Forest (PEF) in Maine, in two <1.0-acre plots established by the USDA Forest Service in the 1970s for a BBD study (Houston et al. 2005). Within those plots, measurements were made annually on numbered beech trees ≥3.5 inches in diameter (i.e., d.b.h., measured at 4.5 ft) starting in 1979. Measurements continued until 1992 and included tree attributes (e.g., d.b.h. and crown condition) and evidence of BBD (e.g., amount of wax from scale insect infestation, tarry spots from fungal infection, and fungal fruiting) on three bole sections (i.e., 0–6.5, 6.5–13, and >13 ft).

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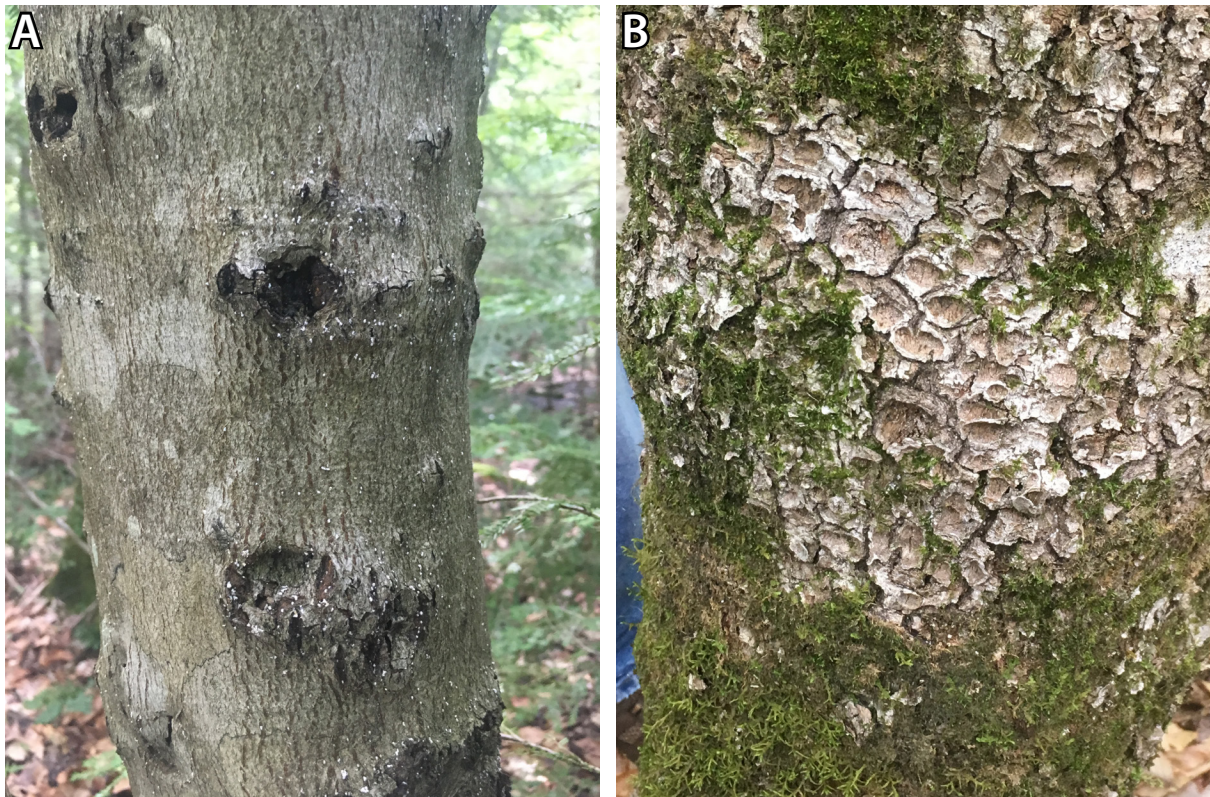


Figure 1.—Trees with BBD with (A) sunken cankers where fungal infection reached the cambium and (B) raised lesions (i.e., delimited cankers) where fungal infection was walled off by the periderm. Sunken cankers are places where the wood is decayed. Raised lesions—which resemble corn flakes or tiny moon craters—are delimited cankers that can be detached with a pocketknife, revealing sound wood. Bark of trees with many raised lesions may thicken and crack over time. Photo A: Courtesy photo by Lauren Keefe, used with permission. Photo B: USDA Forest Service photo by Laura Kenefic.

In 2018, the PEF plots were re-established, and tree measurements resumed for the lower two bole sections using original protocols on one historical and one new plot (i.e., $n = 141$ and 186 trees on plots 102 and 102A, respectively, including ingrowth). Additional measurements since 2018 include proportion of each bole section covered with sunken cankers (i.e., areas where the fungal infection breached the cambium, causing decay) and raised lesions (i.e., areas where the fungal infection was walled off by the periderm; Fig. 1). We used analysis of variance to test for significant differences in historical diameter growth (i.e., change in d.b.h. between 1979 and 2019, plot 102) and current crown dieback (i.e., <10 percent dead branches, 10–50 percent dead branches, and >50 percent dead branches in 2019, plots 102 and 102A) among sunken canker and raised lesion percent-cover categories (1–5, 5–50, 50–75, and >75 percent) on the lower (0–6.5 ft) bole in 2019. Plot was included as a random effect in the crown-dieback model and Tukey’s multiple-range test was used for pairwise comparisons; differences were interpreted using a significance level of 0.10.

RESULTS

Crown dieback was greater (i.e., $p < 0.01$) and diameter growth was lower (i.e., $p = 0.03$) on trees with more than 5 percent sunken canker cover on the lower bole relative to trees with less-sunken canker cover (Figs. 2 and 3). Raised-lesion cover, however, was less clearly related to crown dieback and growth. Though we did find significantly more crown dieback on trees with 5–50 percent percent raised-lesion cover than on those with >75 percent percent raised-lesion cover (i.e., $p = 0.10$), dieback did not differ among other categories (i.e., $p > 0.10$; Fig. 2). Trees with >75 percent lesion cover also exhibited greater growth than those with 5 to 50 percent lesion cover (i.e., $p = 0.08$; Fig. 3).

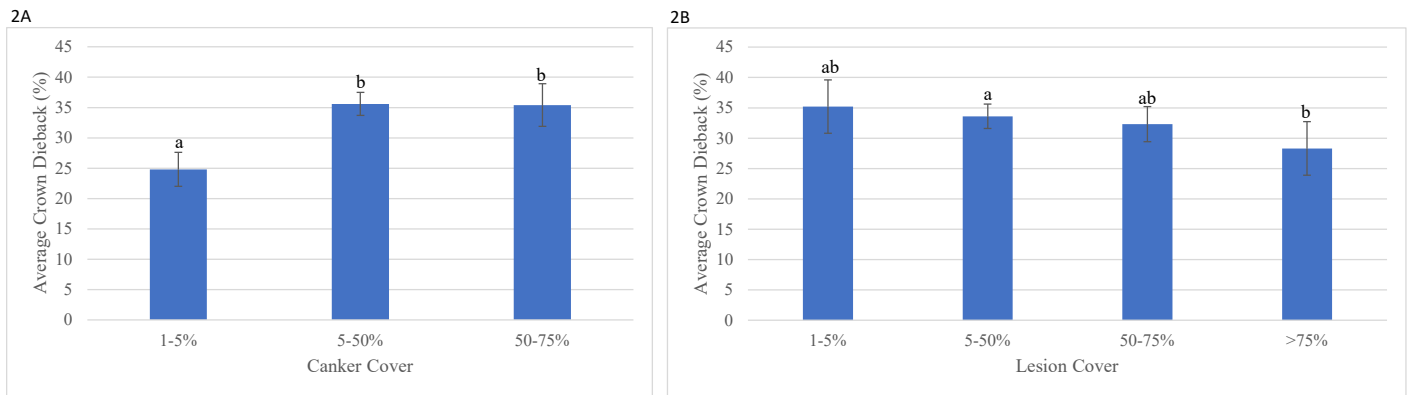


Figure 2.—Relationships between average-crown dieback (percent) and percent of the lower bole of American beech trees in the PEF plots covered with (A) sunken cankers and (B) raised lesions in 2019. Means with different letters are significantly different (i.e., $p \leq 0.10$).

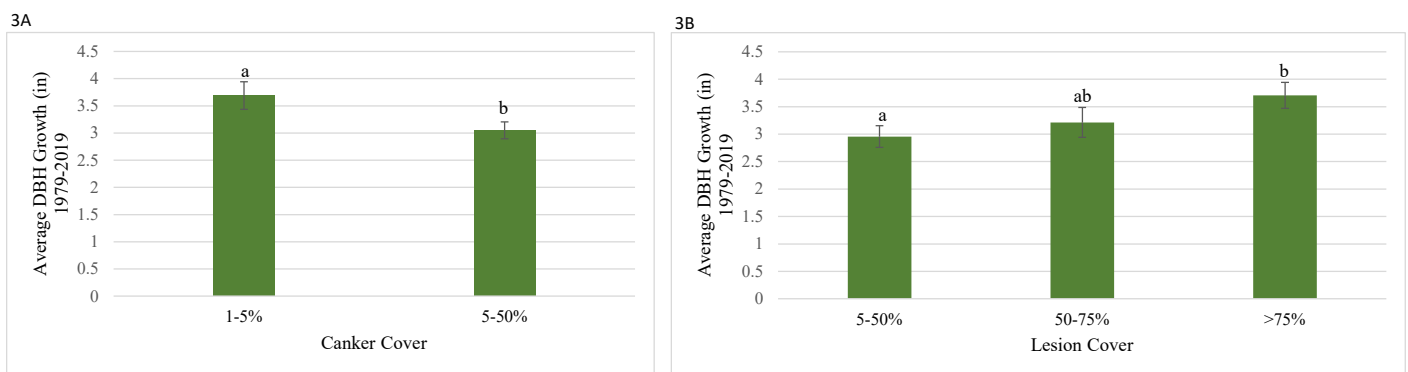


Figure 3.—Relationships between past-diameter growth (i.e., change in d.b.h. between 1979 and 2019 for surviving trees) and percentage of the lower bole of American beech trees in PEF plot 102 covered with (A) sunken cankers and (B) raised lesions in 2019. Means with different letters are significantly different (i.e., $p \leq 0.10$).

DISCUSSION

Preliminary findings suggest that BBD tolerance is not an all-or-nothing condition, but a gradient on which trees exhibit varying proportions of bole area where fungi have either reached or been excluded from the cambium, resulting in sunken cankers or raised lesions. Our hypothesis that proportions of these features indicate degree of BBD tolerance as represented by other measures of tree health was partially supported. Trees with more sunken canker cover (>5 percent) on the lower bole in 2019 grew less over the past 40 years and had poorer crowns. Those with more raised-lesion cover (>75 percent) generally grew more and had better crowns, but those relationships were less distinct. Further investigation is warranted. Most trees in our sample had both sunken cankers and raised lesions; those with more raised-lesion cover likely also had lower sunken-canker cover. Ratios of sunken canker to raised lesion cover on individual trees might better reflect tolerance than either alone; this will be explored in future work.

Monitoring change over time will be critical to determining the potential of using bark condition as an indicator of tolerance, as even tolerant trees likely succumb to the disease eventually. The reasons for differences in raised lesion formation among trees and on a given tree over time merit further study; these might be related to timing of infection relative to the growth period, tree vigor, bark thickness, or other factors (e.g., genetic). Finally, articulating ecological or commodity values (e.g., mast production or wood soundness) of trees with varying degrees of tolerance will help management decision-making.

CONCLUSION

Our preliminary results support the observations of original study PI Houston and others (Ostrofsky and Blanchard 1983) that beech trees exhibit different degrees of tolerance to BBD, and that this tolerance can be observed, in part, as raised lesions on trees infested with the scale insect. Though further work is needed, our findings are an encouraging development for natural resource managers interested in maintaining beech in the aftermath zone (McNulty 2020). Continued work on the idea of “gardening the beech” (Nyland and McNulty 2021) will be strengthened by knowing how to better identify not only resistant but tolerant trees, allowing such trees to be retained if desired.

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Cold Hardiness Considerations for Restoration of Dutch Elm Disease-Tolerant American Elm

Paul G. Schaberg, Paula F. Murakami, Christopher F. Hansen, Gary J. Hawley, Christian O. Marks, and James M. Slavicek¹

INTRODUCTION

Tolerance of Dutch elm disease (DED) is the greatest challenge faced by American elm (*Ulmus americana* L.) populations in North America. However, adaptation to local environmental factors is also an important consideration for breeding efforts of DED-tolerant American elm because the species grows in wetlands and floodplains and was planted in urban settings across a very wide geographic range. For example, American elm grows from Florida to Canada, a territory that spans USDA Plant Hardiness Zones 9b through 2b, with 30-year average annual temperatures ranging from extreme -1 to -42.9 °C. In addition to DED tolerance, it seems likely that matching the cold tolerance of planting stock to the winter temperature extremes of a planting site may also be important for the success of restoration efforts. Questions exist for how genetic lines of DED-tolerant sources currently being tested for species restoration differ in cold hardiness and whether crossing these lines with American elm from colder plant hardiness zones can bolster the cold tolerance of resulting progeny. Here we describe the results of a preliminary test of possible differences in cold hardiness and field-winter injury of shoots of American elm from two maternal sources of DED tolerance crossed with paternal sources of large-residual American elm from three USDA Plant Hardiness Zones (USDA Agricultural Research Service 2018).

METHODS

An American elm restoration trial was established in a field located in the rich soils of the Connecticut River floodplain in Lemington, Vermont. Lemington is in Plant Hardiness Zone 3b, which had an average annual temperature ranging from extreme minimum -37.2 to -34.4 °C from 1976 to 2005. Current-year shoots were collected from two maternal sources of DED tolerance (i.e., Valley Forge and R18-2); four paternal sources from Plant Hardiness Zone 5a; three paternal sources from Zone 6b; and four sources from Zone 6a in December 2016, February 2017, and April 2017. Shoots were transported to our cold-tolerance laboratory where they were chopped into 5-mm internodal segments and subsamples exposed to gradually lower test temperatures ranging from $+5$ to -90 °C. After low temperature exposure, rehydrated shoot segments were tested for electrolyte loss following possible low temperature damage using a multielectro-conductivity bridge. Because cell membranes damaged by freezing injury leak electrolytes, we measured the relative electrolyte leakage (REL) from samples as an indicator of cell injury. The temperature (T_m) at the midpoint of progressive REL increases—that terminate with maximum-electrolyte loss with complete cell death—were used as an estimate of shoot-cold tolerance (Schaberg et al. 2000, 2005; Strimbeck et al. 1995). In addition to laboratory measurements, in July 2017 after leaf-out, winter shoot mortality was visually assessed as dark colored and sunken portions of stems on current-year shoots (Saielli et al. 2014). Deer browse

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Figure 1.—Differences in mean ($\pm$ SE) shoot cold tolerance (T_m) between the three paternal source hardiness zones in midwinter–February 2017. Means with different letters are significantly different at $p \leq 0.05$, based on results from a Tukey HSD test.

was also quantified during July assessments because it was noted that browse pressure was high and could limit the complete accounting of the percentage of terminal shoots damaged by freezing injury.

RESULTS

Shoots were most cold tolerant in midwinter, followed by late fall, and then early spring. Regardless of date, there were no differences in shoot cold tolerance associated with maternal sources of DED tolerance. Indeed, cold tolerance means for Valley Forge and R18-2 sources were near identical on each sample date. In contrast, regardless of date, paternal sources from Zone 5a (i.e., the coldest zone tested) were significantly more cold tolerant than trees from Zone 6b (i.e., the warmest zone) with trees from Zone 6a being intermediate in cold tolerance. This pattern was most pronounced and significant in midwinter (Fig. 1) when ambient air temperatures in the field reached their lowest (i.e., -30.8 °C). July assessments of shoot winter injury in the field confirmed widespread (i.e., >83 percent) of sample trees exhibited freezing injury visible as dead shoot tips with dark sunken lesions on the bark. However, because deer browse damage was so high (with nearly 84 percent of trees in the planting overall showing browse damage), an accurate estimate of the percentage of winter-injured current-year shoots was impossible to assess.

DISCUSSION

Shoot cold tolerance was greatest in winter—a time when greater cold tolerance would be most protective. The lack of differences in maternal cold tolerance may be due to extensive selection for DED-tolerance and a lack of local adaptation to the cold. The overall pattern of cold hardiness among paternal sources was consistent with the origins of their plant-hardiness zones (e.g., trees from sources with parental heritage from the coldest hardiness zones were more cold tolerant than tree from sources from the warmest hardiness zone). Indeed, in winter the difference between cold tolerance means for sources with paternal heritage from the coldest versus the warmest hardiness zones was ~ 7.4 °C, which is within 1 °C of the 8.3 °C average divergence in mean minimum temperature experienced within these zones from 1976 to 2005.

CONCLUSIONS

American elm bred for DED-tolerance are vulnerable to freezing injury that can reduce crown fullness. However, the differences in cold tolerance consistent with the temperature zone of paternal sources that we detected suggest that improvements in local adaptation to the cold can be transferable via selective breeding.

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Oak Wilt Management for Northern Forests

Linda Haugen and Jennifer Juzwik¹

Oak wilt causes significant losses of valuable red oak in forest stands. As this disease is expanding in range, the ability to both detect and recognize oak wilt is important to enable timely application of control measures. Oak wilt is not consistent in its behavior across the range of occurrence. There are known factors that affect disease severity and impact, including soil texture, stand composition, weather/climate, topography, disturbance/management activities, and prevalence/proximity of disease. Understanding these factors is critically important to choose a proper management response. Fortunately, the disease cycle offers several potential points of control, including prevention of overland spread by insect vectors and disruption of root graft spread. The choice of which management actions to apply depends on the resources/tools available, the management objectives, and the many factors that affect disease severity. The USDA Forest Service (FS) and other partners have collected much information about oak wilt over the decades, and changing technology provides new ways to share this information. The FS is currently creating a web application, using ESRI's StoryMap Journal[®] builder (Redlands, CA), that will contain information to help land managers understand their place in the “big picture” (20 state region, Region 9 of the USDA Forest Service) of oak wilt, and thus make better decisions on how to respond. The poster is a synopsis of information to be included in the StoryMap. The anticipated release date is summer 2021 (Fig. 1).

UPDATE

The StoryMap has been finalized and published:

<https://usfs.maps.arcgis.com/apps/MapSeries/index.html?appid=9aec8460770d46aa9d073ae7ec2c783e>

Suggested citation for the published StoryMap:

Haugen, Linda; Juzwik, Jennifer; Chavez, Quinn; Crocker, Susan. 2022. **Oak wilt in the northeastern and midwestern states**. Milwaukee, WI: U.S. Department of Agriculture, Forest Service, Eastern Region. <https://doi.org/10.2737/R9-2022-INT-OakWiltNEMW>.

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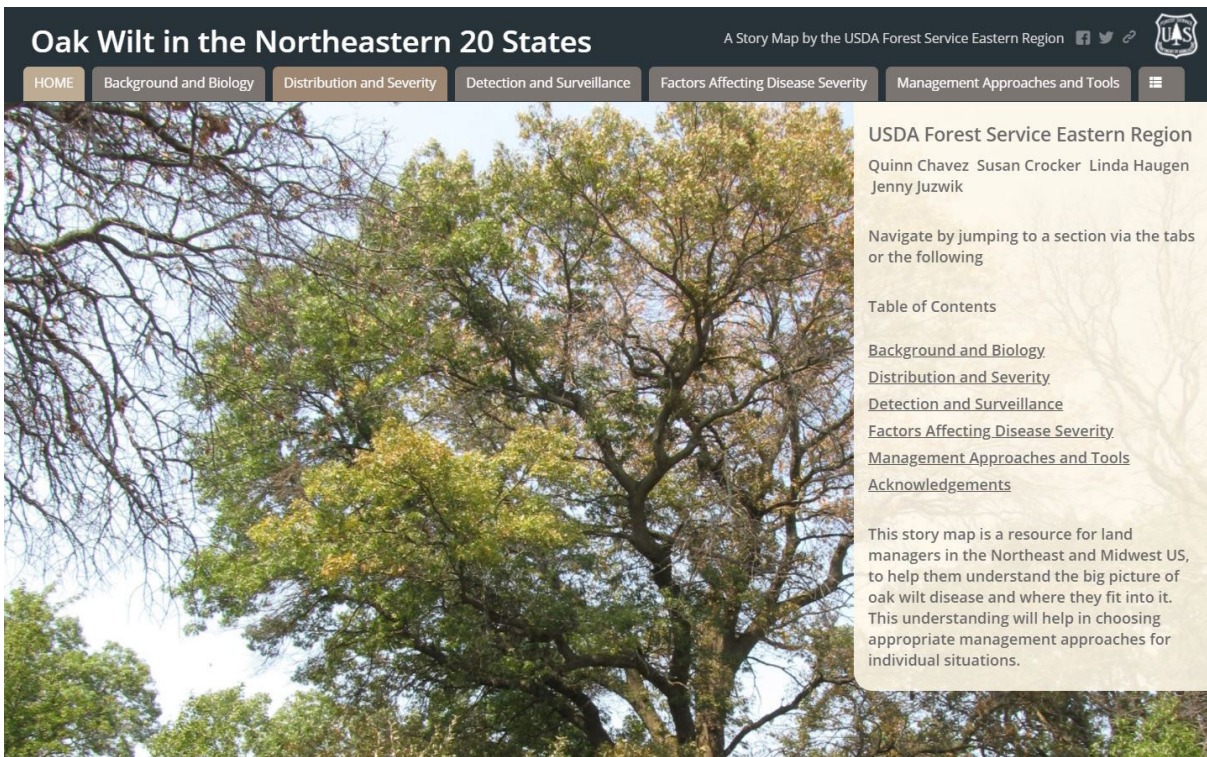


Figure 1.—Home screen of the StoryMap, “Oak Wilt in the Northeastern 20 States.”

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Impacts of a Hickory Decline Event and Implications for Bitternut Hickory

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Abstract.—Between 2010 and 2016, rapid and extensive mortality of bitternut hickory (i.e., 35 percent year⁻¹) was observed within a long-term experimental site in Wisconsin. The purpose of this study was to document and quantify the mortality, investigate stem-density impacts on mortality, and assess remaining hickory regeneration. Similar mortality has been reported in the midwest and northeast United States, and a pathogenic fungus (*Ceratocystis smalleyi* Johnson and Harrington) and hickory bark beetle (*Scolytus quadrispinosus* Say) were identified as the causal agents, herein investigated via a post hoc analysis. Larger hickory stems (i.e., ≥20 cm d.b.h.) experienced higher mortality rates than smaller stems (i.e., 10 to <20 cm d.b.h.). Density (i.e., percent hickory), crown class, and diameter were statistically important in predicting hickory mortality. Maintaining this species is increasingly important, especially as other dominant species, such as ash, are also decreasing. Management actions such as selective thinning will be important in mitigating these rapid hickory declines.

INTRODUCTION

Bitternut hickory (*Carya cordiformis* [Wangenh.] K. Koch) is an important component of many hardwood forests, including sugar maple-basswood forests in northern Wisconsin. The range extends from Quebec to Minnesota, and south to Georgia and Texas. Periodic and severe mortality has occurred historically throughout its range, and more recently within the northeast and midwest United States. Mortality was attributed to the hickory bark beetle (*Scolytus quadrispinosus* Say) and an associated canker pathogen (*Ceratocystis smalleyi* J.A. Johnson and Harrington) (Park et al. 2010, 2013; Park and Juzwik 2014). Extensive mortality of bitternut hickory occurred between 2010 and 2016 within a long-term research site in the Flambeau River State Forest in northern Wisconsin. The objectives of this study were to (1) quantify and characterize the bitternut hickory tree mortality, (2) investigate impacts of stem density on mortality patterns, and (3) assess hickory-regeneration persistence. Post hoc sampling for the hickory bark beetle and *C. smalleyi* was conducted to support the hypothesis that hickory decline was the cause of the extensive mortality.

METHODS

Site Description

The long-term experimental study site is in a second-growth northern hardwood forest dominated by sugar maple, in the southern edge of the Flambeau River State Forest in northern Wisconsin. The “Flambeau Experiment” includes thirty-five 80 × 80 m (i.e., 0.64 ha) permanent plots to test

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seven treatment levels, with five replicates. Treatments are woody debris addition, gap creation, gap creation and woody debris addition, gap creation with deer exclusion, deer exclusion, mechanical disturbance from harvest equipment, and control (Forrester et al. 2013).

Stem Inventory

All trees (stems ≥ 10 cm diameter at breast height [d.b.h.]) in plots were tagged, identified, and mapped. D.b.h., crown class, and status (i.e., live or dead) were measured annually in fall from 2005 to 2010 and in 2016. Saplings (i.e., 0.5 to <10 cm, d.b.h. >1.4 m in height) were measured (i.e., height and d.b.h.) in subplots in 2005, 2010, 2013, and 2016. Woody understory plants were measured in 2010, 2013, and 2016. Species and counts were recorded by height class.

Statistical Analysis

Mortality rates were calculated for the trees in 5 cm diameter classes with the following equation (from Lorimer et al. 2001):

$$mortality = \left(1 - \left(\frac{N_t}{N_o}\right)^{\left(\frac{1}{t}\right)}\right) \cdot 100 \quad (1)$$

Where

N_o = number of trees at first measurement,

N_t = number of surviving trees at next measurement, and

t = time between measurements.

An analysis of variance (ANOVA) with a Tukey's test was used to test for difference in mortality rates by diameter class. Hickory regeneration was assessed with an ANOVA followed by least squares means comparisons to test the significance of the interaction of year by height class.

Using geographic information systems (GIS), four circular areas (i.e., 4, 8, 11, 25 m radii) were delineated around each mapped hickory tree to estimate if density influenced mortality and at what scale. Stem density (percentage hickory) was calculated for each area. Logistic regression was used to model the likelihood of hickory stem mortality testing predictor variables including d.b.h., crown class (canopy or subcanopy), and percentage hickory. All statistical analyses were completed in Statistical Analysis System (SAS) statistical software (i.e., SAS version 9.0, SAS institute, Cary, NC), and significance was determined using an $\alpha \leq 0.05$.

Biotic Agent Identification

In July 2019, three actively dying hickory trees were felled, surveyed, and sampled for biotic agent confirmation. Wood samples were cut and brought back to the laboratory for pathogen identification confirmation using DNA sequencing.

RESULTS

There was an 84 percent reduction of bitternut hickory trees (i.e., ≥ 10 cm d.b.h.) from 2010 to 2016. Mortality rates were higher for hickory compared to other important species (i.e., sugar maple [*Acer saccharum*], American basswood [*Tilia americana*], and ash species [*Fraxinus* spp.]) at the site, at 35 percent year⁻¹ vs. 1 percent year⁻¹. Bitternut hickory trees declined in all size classes, and mortality rates were higher in larger stems compared to smaller stems (Fig. 1).

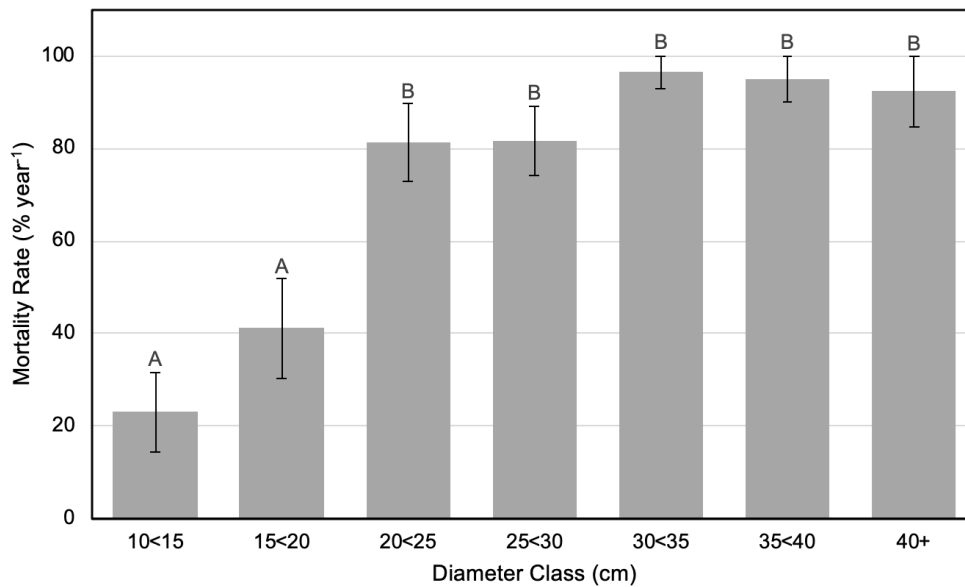


Figure 1.—Mean hickory tree mortality rates from 2010 to 2016. The analysis of variance (ANOVA) of mortality by diameter class resulted in a $p < .0001$, F -value = 15.79, and letters A and B indicate results from a Tukey's test to compare diameter classes ($\alpha = 0.05$ level). Error bars indicate ± 1 standard error.

Table 1.—Logistic regression model equation and parameter estimates for predicting mortality of individual hickory stems using four differently sized circular buffers. Parameter estimate significance from Wald's chi-squared tests denoted using * ($\alpha = 0.05$) and ** ($\alpha = 0.01$). M is log-odds of the probability of mortality, β_i are coefficient estimates, X_1 is crown class (Canopy (D) = 1; Subcanopy (S) = -1); X_2 is percent hickory; and X_3 is d.b.h. (cm).

$$\text{Model: } M = \ln(m/[1-m]) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3$$

Buffer size (radius)	β_0	β_1 (crown class)	β_2 (percent hickory)	β_3 (d.b.h.)	LR ChiSq	H-L (df = 8)	P > ChiSq for H-L
4 m	-1.1018	0.7813**	0.0176**	0.0920**	105.91	4.5695	0.8024
8 m	-1.2583*	0.8040**	0.0367**	0.0875**	112.09	11.2861	0.1860
11 m	-1.1695*	0.7821**	0.0345**	0.0862**	105.85	7.4211	0.4919
25 m	-1.4728**	0.7902**	0.0554**	0.0903**	110.14	5.7647	0.6736

LR ChiSq = Likelihood ratio chi-square statistic, H-L = Hosmer and Lemeshow statistic for testing model goodness of fit (P > ChiSq is statistical significance)

All variables in the logistic regression used to predict likelihood of mortality were significant for each radius modeled (Table 1). All models show that likelihood of mortality increases with increasing d.b.h., a higher (i.e., canopy) crown class, and higher percentage of hickory stems near to the host-hickory stem.

Hickory regeneration density in the <30 cm height class decreased significantly from 2010 to 2016 (i.e., $p = .0012$, F -value = 10.86). Investigation of densities from earlier years revealed that density has been extremely variable, so the decrease cannot be attributed to the same decrease in overstory tree density.

Debarking of sampled hickory trees confirmed the presence of the hickory bark beetle, based on entrance holes and larval galleries. Presence of *C. smalleyi* was confirmed with DNA sequencing.

CONCLUSION

Rapid crown decline of hickory is the likely cause of the bitternut hickory mortality, which is supported by the presence of the biotic decline agents and the consistency of the observed-mortality patterns with other reports in the midwest and northeast United States in the same period. *C. smalleyi* is commonly associated with the hickory bark beetle and has been associated with beetle galleries (Juzwik et al. 2013), although the function of the beetle as a vector has not been proven. Mortality is ultimately caused by vascular dysfunction from multiple beetle attacks, and multiple stem cankers. Drought is known to be an inciting factor in decline diseases and was also observed in the area prior to this mortality event.

Bitternut hickory stems in dominant and codominant canopy positions were almost eliminated from the site following the mortality event, and only 20 percent of stems ≥ 10 cm d.b.h. survived. The likelihood of mortality increased with higher percentages of bitternut hickory within a defined area of a host hickory tree, the host tree d.b.h., and a higher crown class. Stem density is known as a stressor of trees, often increasing susceptibility to insect attacks. In this case, stem density did indeed increase that susceptibility. Hickory regeneration was variable through time, so the decrease in population cannot be attributed to the rapid crown decline of hickory. These results suggest that regeneration does persist shortly following overstory mortality.

Low mortality of the regeneration layer and surviving stems in the mature stem cohort suggest that bitternut hickory can be maintained at the site. The potential for more frequent and intense droughts with climate change could incite mortality events like this to occur more frequently. The loss of even a single species reduces the resilience of a site, especially if other species are under threat as well, such as ash trees facing future emerald ash borer (*Agrilus planipennis* Fairmaire) attack. Managing forests to reduce stress on trees and encourage resilience to insects and pathogens is important to address decline diseases because stressed trees are more likely to succumb to other inciting and contributing factors. The logistic regression model developed here can guide management to reduce stem density, which would minimize the effect of density as a predisposing factor. Mortality is likely in all diameter sizes and canopy positions; however smaller, subcanopy hickory stems are less susceptible to mortality when hickory is in lower proportions. Thinning or selective harvesting techniques can reduce stem density and the proportion of hickory trees, while also increasing biodiversity and heterogeneity in stand species and structure. This further reduces bark beetle populations and the potential for subsequent attacks (Fettig 2012, Knops et al. 1999).

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Exotic Earthworms Impact Forests: Increase Awareness and Integrate Impacts into Forest Management Decisions

Tara L. Bal, Yvette L. Dickinson, and Andrew J. Storer¹

Abstract.—The introduction of nonnative earthworm species into northern hardwood forests negatively affects overall forest health, vegetation dynamics, and soil biogeochemistry. Though they have a long introduction history in some urbanized areas, earthworms continue to invade new forested areas, with new species and additional biomass. Both understory regeneration and overstory canopy trees are negatively impacted by earthworm activity. These “ecosystem engineers” are creating novel systems by affecting both the biotic composition and environmental conditions in northern hardwoods. The condition of the forest floor can be quickly visually assessed during a site visit or timber cruise, but forest management plans rarely record earthworm presence/absence or consider their potential impacts. We argue that earthworms should be explicitly incorporated into hardwood forest management, highlight recommended best-management practices, and describe next steps to fill important research gaps.

BACKGROUND

Although European and Asian earthworms have been repeatedly introduced to northern hardwood forests and new species continue to arrive (Laushman et al. 2018), they have received relatively little research attention (Bohlen et al. 2004a, McCay and Scull 2019). While earthworms naturally move less than eight meters a year, they are rapidly spread by human activity. Common spread events include dumping bait near boat launches, road building activities, and carriage in soil or mud on vehicle tires or shoes (Cameron et al. 2007, McCay and Scull 2019). Earthworm densities, species, and number of species are patchily distributed across invaded regions, and not all species have the same ecological effects (Hale 2013, Shartell et al. 2015). Still, studies since the 1990s have demonstrated significant impacts of earthworm invasions, including significant shifts to soil nutrient cycling and carbon sequestration, decreased pedobiological diversity, and reduced regeneration or poor condition of desirable tree and plant species (e.g., Bal et al. 2018, Bohlen et al. 2004b, Dobson et al. 2017, Ferlian et al. 2018). Further research is required to fully characterize the top-down and bottom-up “cascade complex” caused by earthworms in forest ecosystems (Frelich et al. 2019).

Forest Management Considerations

Awareness of exotic earthworms is increasing among professionals, but this has yet to translate into actionable, applied-decision models and forest management plans rarely record earthworm presence/absence or consider their potential impacts. Although identifying earthworm species can be difficult, this should not be a barrier as other strategies are available for evaluating site condition. Field surveys can visually assess the forest floor, evaluate the depth of organic duff layers, or note earthworm sign (Bal et al. 2018, Loss et al. 2013). Forest management decisions should regularly consider future effects of high earthworm activity as they would any other

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invasive, especially in areas at significant risk of impacts from climate change or where overall forest health is already stressed. Managers will need to continue to think outside of the box of traditional silviculture and be open to experimental trials, as biotic and abiotic environmental factors are influenced by earthworms, creating novel conditions (Seastadt et al. 2008).

Best management practices (BMPs) for exotic earthworms that could be more easily applied in forest management decisions in northern hardwoods are similar to those for introduction prevention of exotic plant species (e.g., LeDoux and Martin 2013). These include:

- Power washing vehicles and harvesting equipment between new field sites
- Installing boot scrubbers at trailheads
- Using local material for road building or road grading activities
- Recording and monitoring presence and impacts or condition of the forest floor
- Public awareness and signage

ONGOING AND RECOMMENDED FURTHER INVESTIGATIONS

Ongoing research highlights the widespread and complex effects of exotic earthworms, from the short-term physiological impacts on individual trees to the long-term impacts on overall forest health. For example, we are currently evaluating sugar maple (*Acer saccharum* Marsh.) dieback and decline in the northern Great Lakes region and relating it to evidence of earthworm activity. Our work takes place in an extensive network of 120 evaluation plots established 12 years ago on public and private lands in predominantly maple forests (Bal et al. 2018). Previous surveys found variable amounts of canopy dieback (i.e., between 0.8 percent to 75.7 percent) and mortality across the landscape (Bal and Storer 2015). Dieback and decline continue to be a concern for federal, state, and industry managers, yet there are not well developed support tools for land managers to anticipate or mitigate earthworm impacts in northern forests. Our current efforts will characterize rate of change in maple dieback and decline and rate of change in forest floor condition—over a decade after initial plots were established—as well as evaluate additional variables potentially being exacerbated by earthworm impacts, including climate change, invasive European Lecanium scale (*Parthenolecanium corni* Bouché) (MI DNR 2017), and deer herbivory. Ultimately this will allow us to create model support tools and improve risk assessment for managers to plan activities more easily with respect to current and predicted exotic earthworm impacts.

Many questions relating to earthworm impacts on long-term forest management still exist. We recommend large, interdisciplinary, experimental silviculture trials. These should combine field observations, field experiments, and lab and greenhouse studies to better understand consequences of earthworm invasion on multiple tree species and identify more efficient mitigation strategies. Studies of currently present introduced earthworm species assemblages can yield valuable insights that may be applied to newly introduced species or those that may be introduced in the future that are potentially more damaging, such as the more recently introduced jumping worms (*Amyntas* spp). It is important to continue supporting efforts to evaluate and understand earthworm invasion progression and understand their relationship to other factors impacting northern hardwood forests.

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CLIMATE CHANGE

A Marked Reduction in the Growth Rate of Sugar Maple Following the Accumulation of Climatic Stress Events in Southern Quebec, Canada

Guillaume Moreau, Alexis Achim, and David Pothier¹

Understanding the influence of climatic variation on forest dynamics is of great ecological and economical interest and is essential to prescribe interventions that will facilitate ecosystem adaptation to climate change. However, the retrospective identification of climatic events responsible for the inter-annual variation of tree growth is challenging, notably because both their duration and their subsequent effect can be highly variable in time. In this study, we aimed to (1) quantify empirically the effect of severe climatic events on the short- and long-term growth dynamics of dominant sugar maple (*Acer saccharum*) trees; (2) compare the effects of different types of climatic events (i.e., drought, winter thaw-freeze, and late frost); and (3) compare the effects of climatic stress events to those of traditional monthly-level climate metrics.

While the analysis from monthly-level metrics first suggested a weak and nonstationary relationship between climatic conditions and tree growth, the analysis from daily-level metrics showed that severe climatic events, and more particularly winter thaw-freeze events, were strongly related to the growth and vigour of sugar maple trees. Our results suggest that the synergic influence of cumulative climatic stress events, which was exacerbated by insect outbreaks during the late 1970s and the early 1980s, induced an important shift in the growth dynamics of sugar maple and its response to variation in climatic conditions.

These results highlight the potential negative impact of global climate change on our capacity to predict stand productivity accurately, especially if climate-sensitive growth models are based on projections of future monthly metrics. Because climatic events are expected to increase both in frequency and severity over the next decades, a general decrease in growth rate and vigour of sugar maple is anticipated in its native range.

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Impacts of Historic Disturbance on Drought Response of Aspen-dominated Forest

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Abstract.—Water limitation is expected to have greater impact on forest growth in the Lake States region in the future, and management may have long-term impacts on how forests respond to this and other potential stressors. We examined the response of aspen-dominated forest growing on droughty, sandy soils to a regionwide drought that occurred in 2012. During July 2018, we stem-mapped, measured, and cored overstory trees across nine replicated treatments at the Long-Term Soil Productivity (LTSP) study installation at Huron-Manistee National Forest in lower Michigan, USA. Annual biomass growth, reconstructed from cross-dated tree ring widths, was used to calculate indices of resistance and resilience and evaluate drought responses at tree and stand scales. Our results indicate little to no direct impact of organic matter removal or compaction on stand-scale growth responses to the 2012 drought, but species, tree size, and density (neighborhood crowding) did influence resistance and resilience.

INTRODUCTION

The Long-Term Soil Productivity (LTSP) study was founded in 1989 to examine the effects of soil disturbance, specifically impacts related to compaction and the removal of organic matter on forest soils and biomass production (Powers et al. 2005). In addition to basic questions about sustaining forest productivity over time, the LTSP study design provides a robust experimental framework for addressing additional questions about management impacts, including whether the severity of initial, stand-replacing disturbance might impact forest response to future disturbance and stress.

Resistance and resilience are commonly used to measure ecological responses to disturbances or other stressors such as drought (Grimm and Wissel 1997). For this study, resistance was defined as the ability of a stand or individual tree to maintain growth during a drought event and resilience as the ability to return to predrought growth rates (Kohler et al. 2010). Previous work has demonstrated that management has potential to influence these responses in other forest types (Kohler et al. 2010, D'Amato et al. 2013), but less is known about aspen-dominated forest ecosystems. The purpose of this study was to address the following research questions related to aspen systems' response to drought at a LTSP site on the Huron-Manistee National Forest: (1) How do soil compaction, organic matter removal, and their potential interaction impact stand-level forest growth response to drought, and (2) How are individual trees responding to drought given factors such as size, species, and crowding in addition to treatment effects.

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METHODS

The study site is on the Huron-Manistee National Forest in northeastern lower Michigan, USA. Forest stands were dominated by quaking aspen² and bigtooth aspen with lesser components of red maple, northern red oak, and white pine prior to harvest in early 1994. Soils at the Huron-Manistee site are acidic and relatively infertile, having developed from outwash sands and composed of 93 percent sand, 6 percent silt, and 1 percent clay (Slesak et al. 2017, Stone et al. 1999).

The impacts of two factors, organic matter removal and compaction, were examined by fully crossing three levels of each, resulting in nine treatments. Levels of organic matter removal included stem-only harvest, whole-tree harvest, and whole-tree plus forest floor removal. Levels of compaction included no additional, moderate (up to 15 percent increase in bulk density), and heavy (up to 30 percent increase in bulk density) (Stone et al. 1999). Each experimental treatment was replicated three times for a total of 27 treatment plots, each 1 acre in area. Sampling for the present study occurred June to August 2018. All live and dead trees greater than 4 inches in diameter at breast height (d.b.h.) that occurred within 0.12-acre circular plots (41.3 ft radius) centered in the existing treatment plots were stem-mapped. Data recorded for each tree included species, crown class, and d.b.h. In addition, increment cores were collected from all living trees greater than 4 inches d.b.h. within a 26 ft radius of each plot center so that neighborhood data could be calculated for all cored trees.

Tree cores were mounted, cross-dated, and measured. Then, annual woody biomass growth was estimated using reconstructed diameters for each year prior to 2018 and allometric biomass equations (Perala and Alban 1993). Estimates of drought response were based on methods described by Kohler et al. (2010). Resistance was quantified as the ratio of growth during drought (2012) to mean annual growth during the 5 years preceding drought (2007–2011). Resilience was the ratio of mean annual growth during the 5 years following drought (2013–2017) to mean annual growth during the 5 years preceding drought. Differences among treatments in stand-level resistance and resilience were tested using analysis of variance (ANOVA). The influence of treatments, tree size, crowding, and species on the drought resistance and resilience of individual trees was assessed using linear mixed effects models.

RESULTS

Our work suggests that treatments (varying combinations of compaction severity with organic matter removal) did not impact drought resistance or resilience at tree- or stand-scales. However, species responses varied and the effect of tree size and neighborhood crowding (related to density) on drought response also varied among species.

Larger trees were generally less resistant to drought than smaller trees (bigtooth aspen was an exception) (Fig. 1). Relative to northern red oak, species that were significantly less resistant to the 2012 drought included red maple, red pine, white pine, bigtooth aspen, and quaking aspen (Fig. 1).

² Scientific names of tree species listed in this paper: quaking aspen (*Populus tremuloides*); bigtooth aspen (*Populus grandidentata*); northern red oak (*Quercus rubra*); red maple (*Acer rubrum*); red pine (*Pinus resinosa*); white pine (*Pinus strobus*); black cherry (*Prunus serotina*); bur oak (*Quercus macrocarpa*); paper birch (*Betula papyrifera*); balsam fir (*Abies balsamea*).

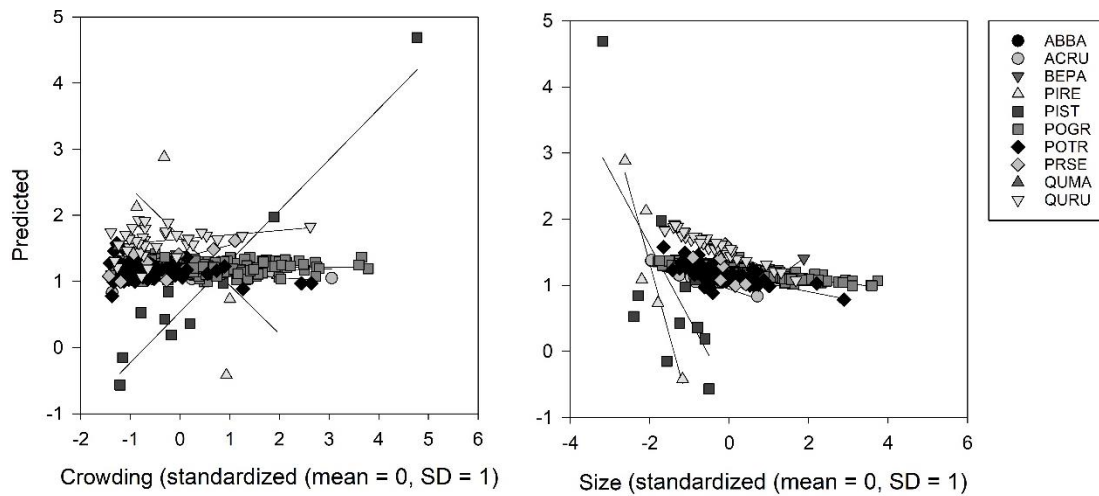


Figure 1.—Plots showing the effects of the interaction between crowding and species and between size and species on drought resistance. Abbreviations: balsam fir (ABBA), red maple (ACRU), paper birch (BEPA), red pine (PIRE), white pine (PIST), bigtooth aspen (POGR), quaking aspen (POTR), black cherry (PRSE), bur oak (QUMA), and northern red oak (QURU).

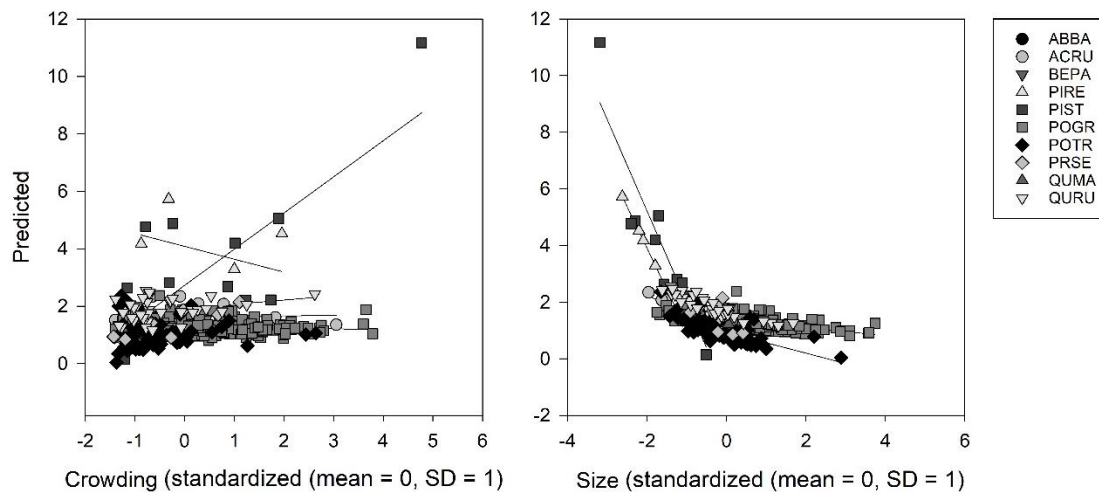


Figure 2.—Plots showing the effects of the interaction between crowding and species and between size and species on drought resilience. Abbreviations: balsam fir (ABBA), red maple (ACRU), paper birch (BEPA), red pine (PIRE), white pine (PIST), bigtooth aspen (POGR), quaking aspen (POTR), black cherry (PRSE), bur oak (QUMA), and northern red oak (QURU).

Northern red oak was more resilient to drought than red pine, white pine, and quaking aspen. Larger trees were significantly less resilient to drought regardless of species, particularly red pine, white pine, and bigtooth aspen (Fig. 2). Crowding negatively affected drought resistance in most species, but generally increased resilience, especially in white pine.

DISCUSSION

Previous studies at this site have shown whole-tree harvest negatively impacts stand-scale aboveground live woody biomass, particularly aspen biomass, compared with conventional, stem-only harvest (Curzon et al. 2014, Curzon et al. 2020). Despite the clear impact of whole-tree harvest on stand productivity, our results suggest that neither whole-tree harvest nor increased compaction directly impacted stand-level response to a drought occurring 18 years later. It is possible that the young age of the stands may have influenced responses as tree age is known to

affect climate-growth relationships. Potential recovery from forest tent caterpillar (*Malacosoma disstria*) defoliation during a recent outbreak (2008–2010) may have also influenced our ability to quantify the response of quaking and bigtooth aspen to drought as both response indices quantified (resistance and resilience) rely on comparisons of diameter growth during, after, and prior to the drought year.

As observed in other forest types, tree size influenced drought response in these forests as did neighborhood conditions. Trees in more crowded neighborhoods, or those with a greater density of neighboring trees (with larger and closer trees weighted more heavily) generally exhibited less resistance to drought as expected based on observations in other forest types (Bottero et al. 2017, D'Amato et al. 2013). However, crowding generally had a positive influence on the resilience of individual trees to drought, meaning that the ratio of post-drought growth to predrought growth was higher in trees within denser neighborhoods.

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Climate Adaptation Treatment Impacts Adaptability of Natural Regeneration in Red Pine-dominated Ecosystems

Lewis J. Wiechmann, Miranda T. Curzon, and Brian J. Palik¹

Abstract.—Climate change may require foresters to adapt management in order to maintain healthy, functional forests. We present the effects of experimental climate adaptation treatments on species diversity and adaptability of natural tree regeneration 5 years following implementation in red pine-dominated ecosystems in north central Minnesota. Treatments included resistance, resilience, and transition. Each adaptation treatment increased tree species diversity and richness over the passive control treatment. The transition treatment resulted in the greatest adaptability, quantified as a composite index that integrated disturbance response and life history traits. Our results suggest the transition treatment positively impacted recruitment of native tree species that are adapted to future climate conditions as intended, including species such as northern red oak, red maple, and black cherry. The implication is that natural regeneration can be an important factor in achieving climate adaptation objectives.

INTRODUCTION

Increasingly, forest managers face the challenge of regenerating tree species under current conditions that are also able to adapt to a range of anticipated climate conditions in the long term. In the Great Lakes region of the United States and Canada, warmer temperatures, along with reductions in growing season precipitation, are anticipated to reduce habitat for many tree species, such as red pine (Swanston et al. 2018). Models also predict an increase in abundance and range for other species expected to become more competitive under the projected future climate conditions, such as red maple and northern red oak (Iverson et al. 2019). To address the challenges posed by these changes, the Adaptive Silviculture for Climate Change (ASCC) long-term study site at the Cutfoot Experimental Forest in north central Minnesota, USA, is assessing the impacts of three climate adaptation approaches (resistance, resilience, and transition) and a “no action” passive control treatment in red pine-dominated forest ecosystems (Nagel et al. 2017). Five years following treatment implementation, we evaluated how these climate adaptation approaches have influenced natural regeneration and the understory woody community in terms of species abundance, community composition and diversity, and whether silviculture can be used to encourage natural regeneration of species that are more adaptable to future climate.

METHODS

Natural regeneration of trees and shrubs was sampled within 170 plots from May to August 2019 across the entire study area (200 ha), including all five replicates of the four treatments. The passive treatment served as the study control, representing a no action approach to management. The resistance treatment consisted of a stand-wide thinning to a residual basal area of approximately 25 m² ha⁻¹. For the resilience treatment, 15 to 20 percent of each stand was harvested in 0.2-ha gaps and scarified with a harrow disc. Another 15 to 20 percent of each stand was reserved in 0.2 ha-“skips” (not harvested), and the remaining 60 to 70 percent was thinned to

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a residual basal area of 25 m² ha⁻¹. The transition treatment involved harvesting 0.2-ha gaps across 15 to 20 percent of each stand while the remainder of the stand was thinned to an average of 15 m² ha⁻¹ with scarification applied throughout. While artificial regeneration is part of the resilience and transition treatments, we did not include it in our study.

Species density, frequency, and biomass estimates calculated from field measurements were then used to calculate a species relative importance index at the stand-scale. Using previously published species-specific adaptability scores based on a composite of life history and disturbance response traits (Matthews et al. 2011) and the relative importance index, we calculated a community weighted mean of adaptability for natural tree regeneration within each stand. Species richness and diversity (as defined as the Shannon Diversity Index; H') were also calculated for each stand. Differences in species diversity, species richness, abundance of individual species, and adaptability of the regenerating tree community relative to the passive treatment were then tested with analysis of variance.

RESULTS

All climate adaptation treatments differed from the passive control treatment in terms of tree species diversity and richness. Total woody species diversity (including shrub and tree regeneration) also differed among treatments (F=6.42, p=0.008), but only resilience differed from the passive control. The change in relative importance of individual species (from the passive control treatment) varied among treatments as well. This includes black cherry², which was more abundant in resistance, resilience, and transition treatments (Fig. 1). Lastly, change in relative adaptability from the passive control varied significantly among treatments (F=7.138, p=0.017), with mean adaptability of the transition treatment exceeding means observed for both resilience and resistance (Fig. 2).

DISCUSSION

Natural regeneration is an important component of sustainable forest management, key to ensuring productive forest ecosystems for future generations, particularly when resources are unable to support artificial regeneration. Therefore, knowing what species establish naturally following the types of adaptation treatments we examined, including those that combine overstory manipulation with site preparation (e.g., scarification), will inform strategies and implementation. Although planting seedlings may be a more predictable way to regenerate stands adapted for future conditions, our results suggest relying on natural regeneration may be a viable option. Each of the climate adaptation treatments we tested (resistance, resilience, and transition) increased naturally regenerated tree species diversity and richness relative to the passive control, while offering different benefits (e.g., woody species diversity versus adaptability) in terms of climate adaptation.

Greater species diversity will likely increase ecosystem resilience to future disturbance (Webster et al. 2018), in part because of associated increases in response diversity, the variability in tolerances to different stressors or disturbances with potential to cause change among species with similar functions (Elmqvist et al. 2003). The resilience treatment resulted in the greatest difference in overall woody species diversity from the three other treatments; however, mean adaptability of the regenerating tree community was greatest within the transition treatment. Soil scarification, combined with lower residual basal area and varied structure across the transition treatment may have aided in the recruitment of species scoring higher on the adaptability index, including several hardwood species (e.g., red maple, northern red oak, and black cherry) in this historically pine-

² Scientific names of tree species listed: red pine (*Pinus resinosa*); black cherry (*Prunus serotina*); red maple (*Acer rubrum*); northern red oak (*Quercus rubra*).

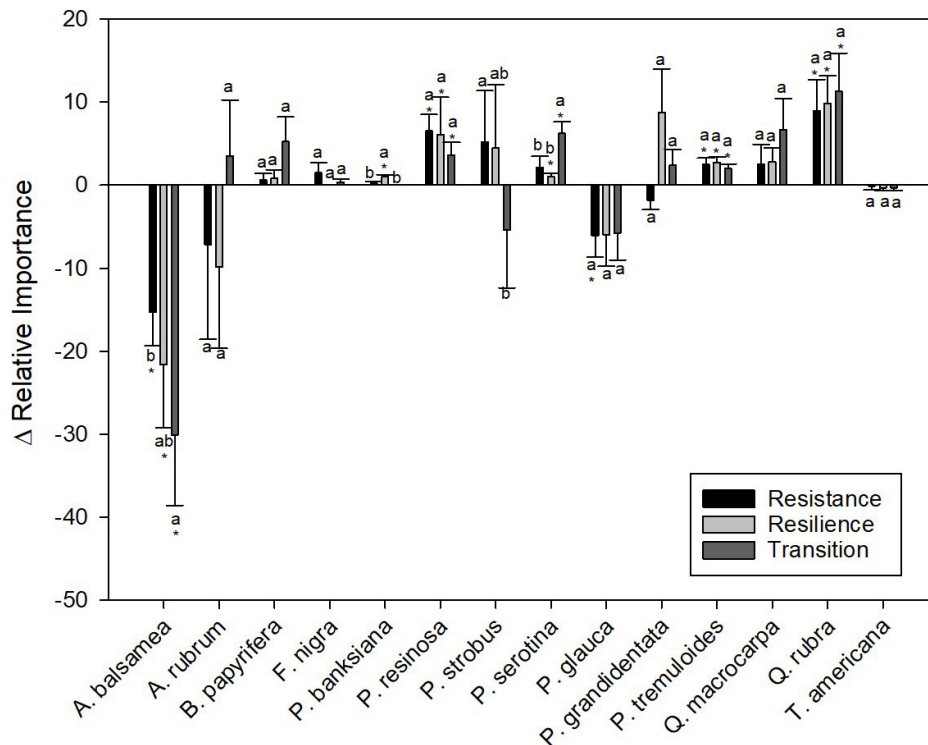


Figure 1.—Change (Δ) in relative importance of natural regeneration compared to the passive control. Bars with different lower-case letters are statistically different. An asterisk indicates a significant change from the passive treatment ($p < 0.1$). Error bars indicate a 68 percent confidence interval around the estimate. Scientific names of tree species listed on the x axis: balsam fir (*Abies balsamea*); red maple (*Acer rubrum*); paper birch (*Betula papyrifera*); black ash (*Fraxinus nigra*); jack pine (*Pinus banksiana*); red pine (*Pinus resinosa*); eastern white pine (*Pinus strobus*); black cherry (*Prunus serotina*); white spruce (*Pinus glauca*); bigtooth aspen (*Populus grandidentata*); quaking aspen (*Populus tremuloides*); bur oak (*Quercus macrocarpa*); northern red oak (*Quercus rubra*); basswood (*Tilia americana*).

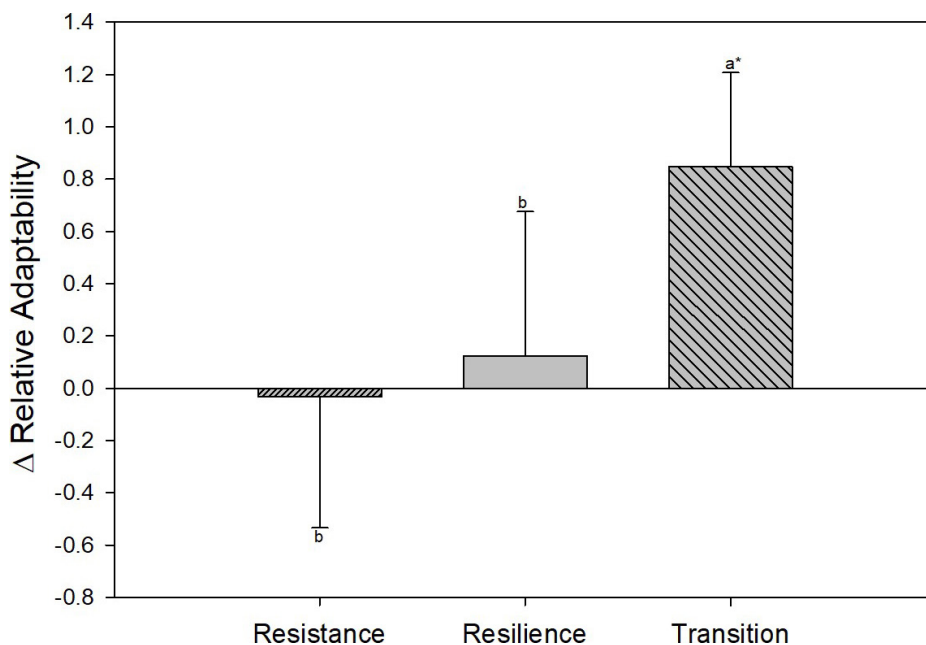


Figure 2.—Change (Δ) in relative adaptability compared to the passive control. Bars with different lower-case letters are statistically different based on Tukey-adjusted pairwise comparisons ($p < 0.1$). An asterisk indicates a significant change from the passive control ($p < 0.1$). Error bars indicate a 68 percent confidence interval around the estimate.

dominated ecosystem. Results indicate that the resilience and transition treatments are moving stands toward greater representation of future-adapted tree species. Our work suggests that climate adaption objectives may be achieved through natural regeneration in addition to or in lieu of artificial regeneration when financial or time resource constraints exist.

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Climate Change Vulnerability Assessment at Apostle Islands National Lakeshore

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INTRODUCTION

Apostle Islands National Lakeshore (APIS) is one of the few archipelagos in Lake Superior, the largest freshwater body in the world. Sandstones deposited about 600 million years ago form the foundation for several rare features such as clay bluffs, rock ledges, coastal wetlands, and sandscapes (sandspits, cusped forelands, tombolos). A double tombolo on Stockton Island supports a globally critically imperiled Great Lakes Barrens feature. Rare communities include boreal, krummholz, and old growth forests that support eastern hemlock, yellow birch, northern white-cedar, and Canada yew², a species nearly extirpated on the mainland. Numerous state endangered (5), threatened (13), and special concern (26) plant species are also present. These numerous features and species are character-defining for the park and, as such, are highly significant.

The park's marine context suggests that some of its natural communities, features, and species face unique potential impacts from climate change. Changes in local climate are not only evident but dramatic —Lake Superior is “one of the fastest-warming lakes on the planet” (MPR 2016) of 235 lakes studied (O'Reilly et al. 2015), at 2 °F/decade – “three times the global average” (MPR 2016). The lake's temperature has increased twice as fast as the surrounding air (Austin and Coleman 2007) and the resultant change in the water-air temperature gradient has increased wind speeds almost 5 percent per decade since 1985 (Desai et al. 2009). These changes in both mean conditions and disturbance regimes threaten the park's highly exposed terrestrial natural communities and features in part because of the naturally fragmented landscape—the park's 21 islands include 160 miles of shoreline.

In addition, the park is in a region experiencing serious rain events at a greater rate in recent years. Two 100-year events (2011 and 2016), a 500-year event (2012), and most recently, a 1000-year event (2018) have occurred. Impacts to natural resources in the park include breached lagoons, loss of beach habitat, and increased tree blowdown, with potential for natural disturbance regime alteration over time.

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² Scientific names of tree species are in appendix.

Considering these resources and the threats posed by climate change, we developed the following questions: (1) How are rare and character-defining terrestrial features and natural communities of the park vulnerable to climate change? How does the park's island setting influence these vulnerabilities? (2) Could the park serve as important refugia for some terrestrial vegetation species or community types? (3) Will Lake Superior function as a barrier to northward migration of species, and what are the implications? (4) How will increasing lake temperatures and wind speeds alter the natural disturbance regimes in the park? What are the implications for both wind and fire processes?

METHODS

We worked with the Northern Institute of Applied Climate Science (NIACS) to complete a vulnerability assessment (Janowiak et al. 2014). The process included a literature review to identify observed and projected change in climate and physical processes in the park, data modeling, and a workshop with a group of experts familiar with the park to validate information. Vulnerability was defined as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the impacts and adaptive capacity of a system. For this assessment, a system may be considered to be vulnerable if it is at risk of a decline in health, a decline in extent, a substantial change in identity, or a decline in crucial ecosystem functions.

Eleven habitats that define the park were identified for use in the assessment and they include:

- Beaches and dunes
- Boreal forest (including krummholtz)
- Coastal wetlands
- Deep ravine forests
- Erodible maritime bluffs
- Great lakes pine forests and barrens
- Interior alder thickets
- Interior peat swamps and bogs
- Mixed conifer hardwoods
- Rock cliffs and ledges
- Upland hardwood forest

For each habitat, characteristic tree and shrub species were identified, along with ecosystem drivers, and current stressors. Modeling projected to the end of the century, used both a national statistically downscaled model (for Representative Concentration Pathways 4.5 and 8.5 scenarios) and a regional dynamically downscaled model, data from the Climate Change Tree Atlas (Prasad et al. 2014), and USDA Forest Inventory and Analysis (FIA), and modeled a 1 × 1-degree area. Several parameters were incorporated into the modeling effort including temperature, precipitation, growing season length, extreme precipitation, extreme heat, extreme cold, snowfall (lake effect, too), drought, lake temperature, lake ice, lake levels, lake currents, wave action, wind speed and direction, summer storms, and cloud cover. All information was available to expert panel members prior to a workshop. During that effort panel experts identified the vulnerability of each habitat and the confidence in the available evidence and agreement among the information (Figs. 1 and 2). The process solicited individual input first and then sought concurrence among panel members.

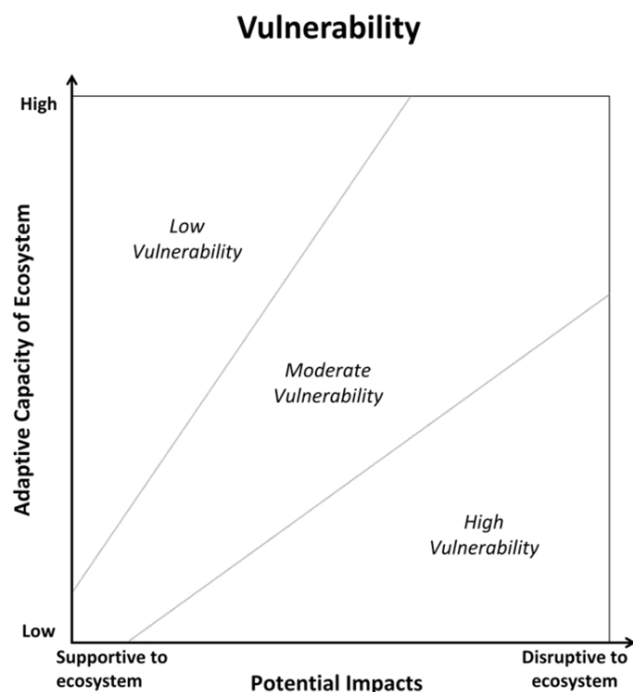


Figure 1.—Chart used to consider and range climate change vulnerability of terrestrial Apostle Islands ecosystems, illustrating the relationship among potential impacts and adaptive capacity. Modified from Swanston et al. 2011.

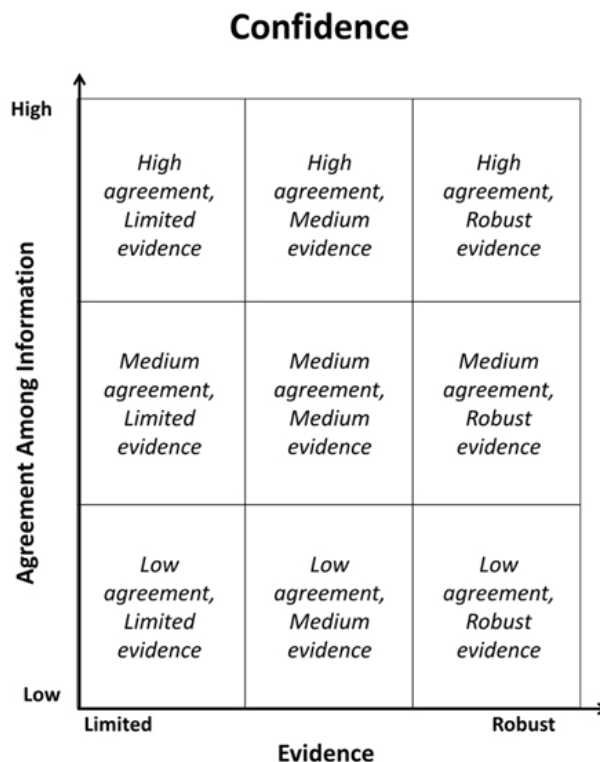


Figure 2.—Confidence determination diagram used in the assessment workshop. Adapted from Mastrandrea et al. 2010.

RESULTS

Annual temperatures are projected to increase 6.4 °F under RCP 4.5 and 11.2 °F under RCP 8.5 with the greatest increase in winter (7.7 to 13.3 °F). Extreme temperatures are projected to increase as well with 20–30 days per year at temperatures greater than 95 °F. Projected change in precipitation ranges from 2.8 inches (RCP 4.5) to 4.2 inches (RCP 8.5) with the greatest change in spring (1.3 to 2.3 inches). Extreme precipitation events are projected to continue to increase in frequency. Additional climate projections are available in the full report (available at <https://irma.nps.gov/DataStore/DownloadFile/640012>).

Several forest species are projected to lose suitable habitat by the end of the century. Mountain maple, pin cherry, and serviceberry will lose nearly all suitable habitat in the area analyzed. Balsam fir, black ash, black spruce, northern white-cedar, quaking aspen, sugar maple, and yellow birch will experience lesser declines. Eastern hemlock, jack pine, paper birch, red maple, tamarack, and white spruce are predicted to experience less than a 20 percent change in suitable habitat under both climate scenarios. Additional projections are available in the full report (available at <https://irma.nps.gov/DataStore/DownloadFile/640012>).

The adaptive capacity and vulnerability of each of the 11 ecosystems is shared in Table 1 along with information related to confidence in the data available. All systems were identified as having at least moderate adaptive capacity. However, boreal forests, coastal wetlands, and rock cliffs and ledges were considered to have moderate-high vulnerability. Boreal forests in the park are at the southern edge of their range and species are susceptible to warming conditions. Coastal wetlands and rock cliffs and ledges are vulnerable to impacts from lake disturbances. These impacts can also alter the temperature and nutrient ranges of coastal wetlands.

Table 1.—Determinations of climate change vulnerability and confidence for the 11 terrestrial Apostle Islands ecosystems. Potential impacts are rated on a scale from “disruptive” to “supportive,” and adaptive capacity is rated on a scale from low to high. Evidence is rated on a scale from limited to robust, and agreement is rated on a scale from low to high.

Ecosystem	Potential Impacts	Adaptive Capacity	Vulnerability ^a	Evidence	Agreement	Confidence ^b
Beaches and dunes	Moderate	Moderate-High	Low-Moderate	Moderate	Moderate	Moderate
Boreal forests	Disruptive	Moderate	Moderate-High	Limited-Moderate	Low-Moderate	Low-Moderate
Coastal wetlands	Disruptive	Moderate	Moderate-High	Limited-Moderate	Low-Moderate	Low
Deep ravine forests	Moderate	High	Low-Moderate	Moderate	Moderate	Moderate
Erodible maritime bluffs	Moderate-Supportive	High	Low	Moderate	Moderate-High	High
Great Lakes pine forests & barrens	Moderate-Supportive	Moderate-High	Low	Limited-Moderate	Moderate	Moderate
Interior alder thickets	Moderate-Supportive	High	Low	Moderate-Robust	High	High
Interior peat swamps and bogs	Disruptive-Moderate	High	Moderate	Moderate	Moderate	Moderate
Mixed conifer hardwoods	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
Rock cliffs and ledges	Disruptive-Moderate	Moderate	Moderate-High	Moderate	Moderate	Moderate
Upland hardwood forests	Moderate	Moderate-High	Low-Moderate	Moderate	Moderate-High	High

^a Potential impacts and adaptive capacity are combined to reach a vulnerability determination (low to high), following Figure 1.

^b Evidence and agreement are combined to reach a confidence determination, following Figure 2.

Through the process of completing this assessment, it was possible to consider the supplemental questions posed by National Park Service managers.

Question 1: How are rare and character-defining terrestrial features and natural communities of the park vulnerable to climate change? And how does the park’s island setting influence these vulnerabilities?

At the broader scale, yellow birch and northern white-cedar are expected to experience a small decline in suitable habitat over the next century, and suitable habitat for eastern hemlock is not expected to change significantly. Canada yew is expected to decline across Wisconsin, as the projected future suitable climate range of the species overlaps with the current range by only 7 percent (Spalink et al. 2018). However, these species may be expected to perform better within the Apostle Islands than on the mainland, because they are currently regenerating well, and the current low deer herbivory will likely continue.

The island context of the park is a critical factor to consider when assessing the vulnerability of park features to climate change. During the expert panel workshop, our conclusions about climate change vulnerability often hinged on the group’s understanding of how ecosystems in the Apostle Islands might differ from those found on the mainland, and how climate change effects might be modified in some way by the park’s local context.

Question 2: Could the park serve as important refugia for some terrestrial vegetation species or community types?

The Apostle Islands hosts more plant species with narrow distributions than anywhere else in Wisconsin (Spalink et al. 2018), including several arctic disjunct species. This suggests that it has been and is currently functioning as a climate refugium (Morelli et al. 2016). Similarly, the Apostle Islands contain plant species that are much less common on the mainland, such as Canada yew. So the Apostle Islands are clearly also acting as a refugium from certain kinds of ecosystem disturbances, such as deer herbivory. This is likely to continue into the future.

Question 3: Will Lake Superior function as a barrier to northward migration of species, and what are the implications?

It is reasonable to conclude that Lake Superior will continue to function as a barrier to northward range expansion of some species. Looking at the list of tree species that are anticipated to have newly available suitable habitat in the Apostle Islands by the end of the century, several have large seeds that would be less likely to disperse across open water, such as hickory and oak species. Wind-carried and bird-dispersed plants, however, may be able to colonize the islands as plant communities change on the mainland. Plants with larger seeds that are expected to increase in suitable habitat on the mainland will likely not reach the islands without intentional management intervention.

Question 4: How will increasing lake temperatures and wind speeds alter the natural disturbance regimes in the park? What are the implications for both wind and fire processes?

The workshop panel experts were not confident that there will be a large increase in wildfire activity across most of the park's acreage. The mixed-conifer hardwoods matrix forest is not expected to have substantially more wildfire because the relatively flat topography and clayey soils are expected to remain relatively moist in most conditions. Also, the island setting will prevent fires from spreading very far. More fuel buildup due to blowdown events or pest outbreaks could create conditions for stand-replacing fires on individual islands.

The expert panel also discussed how interactions among several factors could change shoreline processes and disturbance from storms and wave action. We generally expect that shorelines in the Apostle Islands, including sandscapes, coastal wetlands, erodible bluffs, and rock cliffs, will experience more disturbance from wave action. This may be particularly evident in winter months as the islands are more exposed to strong storms without protective ice cover along the shoreline.

As managers continue to grapple with these questions, locally relevant information will be essential to help guide their decisions and weigh potential options. We hope that this assessment will provide a useful foundation for park managers, conservation partners, and members of the public who value the Apostle Islands.

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APPENDIX

Scientific names for the tree species listed in this paper.

Common name	Genus	Species
Balsam fir	<i>Abies</i>	<i>balsamea</i>
Black ash	<i>Fraxinus</i>	<i>nigra</i>
Black spruce	<i>Picea</i>	<i>mariana</i>
Canada yew	<i>Taxus</i>	<i>canadensis</i>
Eastern hemlock	<i>Tsuga</i>	<i>canadensis</i>
Jack pine	<i>Pinus</i>	<i>banksiana</i>
Mountain maple	<i>Acer</i>	<i>spicatum</i>
Northern white-cedar	<i>Thuja</i>	<i>occidentalis</i>
Paper birch	<i>Betula</i>	<i>papyrifera</i>
Pin cherry	<i>Prunus</i>	<i>pensylvanica</i>
Quaking aspen	<i>Populus</i>	<i>tremuloides</i>
Red maple	<i>Acer</i>	<i>rubrum</i>
Serviceberry	<i>Amelanchier</i>	<i>spp.</i>
Sugar maple	<i>Acer</i>	<i>saccharum</i>
Tamarack	<i>Larix</i>	<i>laricina</i>
White spruce	<i>Picea</i>	<i>glauca</i>
Yellow birch	<i>Betula</i>	<i>alleghaniensis</i>

The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

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Lessons Learned from Climate Adaptation Projects in Northern Hardwood Forests

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Climate change will present challenges for northern hardwood forests through the coming century. Many land managers are seeking information and resources to inform forest management activities given a wide range of potential future conditions. The field of climate adaptation is growing rapidly, with increased information available regarding the vulnerability of forests to climate change, tools for considering climate change in management planning and decision making, and management options to support adaptation to future conditions.

Climate change vulnerability assessments for the midwest and northeast United States indicate that forest vulnerability varies regionally due to differences in projected future climate, species range changes, and nonclimate stressors. Many northern hardwood tree species are expected to lose suitable habitat at the southern extent of their species range and in locations where climate change exceeds biological thresholds (Peters 2020, Prasad et al. 2020). For instance, central Appalachian northern hardwood forests are rated as highly vulnerable because warmer and drier climate conditions and enhanced disturbance are expected to increase stress on several dominant species that are at the southern extent of their range in this region (Butler et al. 2015). Northern hardwood forests in the mid-Atlantic region have moderate-high vulnerability, largely due to interactions among climate change and other stressors present in this highly populated and heavily fragmented landscape (Butler-Leopold et al. 2018). In comparison, northern hardwood forests in the Upper Great Lakes and Northeast are rated as having low-moderate levels of vulnerability given the expectation that regional forests and tree species have a greater capacity to cope with climate change impacts in the absence of major disturbance (Handler et al. 2014a, Handler et al. 2014b, Janowiak et al. 2018, Janowiak et al. 2014).

Two complementary adaptation efforts support natural resource professionals integrating climate change information into management by providing decision-support tools, technical assistance, and real-world demonstrations. The Climate Change Response Framework (CCRF; www.forestadaptation.org) is a collaborative, cross-boundary approach among scientists, managers, and landowners to incorporate climate change considerations into natural resource management. In addition to the aforementioned assessments, CCRF tools and resources include an Adaptation Workbook, multiple menus of adaptation strategies, and a network of more than 500 adaptation

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demonstrations featuring real-world management projects that have used the Adaptation Workbook and menus (Swanston et al. 2016). The Adaptive Silviculture for Climate Change (ASCC; www.adaptivesilviculture.org) network of experimental trials provides robust silvicultural experiments to test adaptation options for resistance, resilience, and transition in various forest types in the United States and Canada (Nagel et al. 2017). Together, projects implemented through CCRF and ASCC serve as critical examples of forest adaptation, and evaluation of these projects can inform adaptive management in northern hardwood forests and other ecosystem types.

Adaptation projects in northern hardwood forests vary widely based on numerous local factors, such as landowner goals, site and soil conditions, legacies of past management, forest species composition and age structure, climate change impacts, and nonclimate stressors. Simultaneously, adaptation projects in northern hardwoods often share similar characteristics based on a manager's aim to resist climate change, increase ecosystem resilience, or facilitate transitions toward new forest assemblages (Table 1). ASCC study treatments in northern New Hampshire, described below, illustrate the trend seen across many adaptation projects in northern hardwood forests where the modification of gap sizes and harvest levels are used to mimic natural disturbance and create light conditions to facilitate regeneration of desired species: shade tolerant mesic species in resistance; mid-tolerant, future-adapted, native species in resilience; and future-adapted, mid- and intolerant species in transition.

Adaptation projects are fundamentally experimental given that controls for a no-climate-change situation do not exist, making monitoring and evaluation of these projects critical for adaptive management. ASCC trials provide an opportunity to evaluate the effectiveness of adaptation treatments in an experimental framework. Additionally, the use of climate-informed inventory has been used at adaptation demonstration sites like Caroline Lake Preserve in northern Wisconsin to inform management decisions and evaluate outcomes (Janowiak et al. 2017).

ADAPTIVE SILVICULTURE IN NORTHERN HARDWOODS

The ASCC northern hardwoods project takes place at the Dartmouth Second College Grant (SCG), an unincorporated township of 10,800 ha in northern New Hampshire owned and managed by Dartmouth College. In the 160-ha research area, elevations vary from 484 to 650 meters. Mean annual temperature ranges from -12 °C (January) to 17 °C (July) and annual precipitation is 117.1 cm (NOAA 2020). Soils are coarse loamy glacially derived tills (Jevon et al. 2019, NRCS 2020). The research site is a northern hardwood forest, dominated by sugar maple and significant components of yellow birch and beech. The adaptation treatments were codeveloped with a group of scientists and managers over a multi-day workshop within the resistance, resilience, and transition framework (Table 1) and were implemented in 2017.

FOREST COMPOSITIONAL CHANGE

Central to the development of the adaptation treatments are concepts of structural, functional, and compositional diversity that increase adaptive capacity. Forests containing a diversity of species and functional traits are more likely to have some species or traits that can persist through novel disturbance and species-diverse temperate forests have shown greater resistance to drought than less diverse forests (Jactel et al. 2017). A diversity of species, age, and size classes may confer some protection from wind events, as well as insect and fungal pests (Foster 1988, Gerlach et al. 2011, Jactel and Bockerhoff 2007). Further, diverse stands have numerous pathways to withstand and recover from novel disturbance (Fahey et al. 2018, Messier et al. 2014). Varying levels of connectivity between different structural and compositional elements also contribute to adaptive capacity and understanding the arrangement of elements is an important component of

Table 1.—Selected climate change impacts and adaptation options in northern hardwood forests

Factor	Description		
Forest type	Northern Hardwoods		
Climate change impacts	- Higher temperatures and altered precipitation can increase heat stress, moisture stress, and drought risk in this mesic forest type. - Heavy precipitation events increase risk of overland flows and erosion on slopes, and flooding in low-lying areas - Shifts in tree species distributions in response to changing conditions. - Increases in insect pests and pathogens as agents move northward or respond to other changes in weather and climate - Interactions with other stressors, such as deer browse, invasive earthworms, and invasive plants - Altered disturbance regimes, including potential for increased damage from extreme storms and wind		
Adaptation options	Resistance	Resilience	Transition
Definition (Millar et al. 2007, Nagel et al. 2017)	Actions that improve the defenses of the forest against anticipated change or directly defend the forest against disturbance to maintain relatively unchanged conditions.	Actions that accommodate some degree of change but encourage a return to a prior condition or desired reference conditions after disturbance.	Actions that intentionally accommodate change and enable ecosystems to adaptively respond to changing and new conditions.
Goal (Nagel et al. 2017)	Maintain relatively unchanged conditions over time.	Allow some change in current conditions, but encourage an eventual return to reference conditions.	Actively facilitate change to encourage adaptive responses.
Example management actions based on CCRF adaptation demonstrations	Thinning, single-tree, or small-group selection to maintain current shade-tolerant species composition. Control of competing vegetation or animal browse to support native plant community.	Small-group selection or small-patch harvests to increase native mid-tolerant associate species such as yellow birch Natural regeneration or planting to increase representation of locally associated species, such as red oak or white pine. Control of competing vegetation or animal browse to support native plant community.	Irregular shelterwood, large gap/patch cuts, or other harvests to alter composition toward future-adapted species. Natural regeneration of future-adapted species with a local seed source. Planting of future-adapted species, including assisted migration species. Control of competing vegetation or animal browse to support development of future-adapted assemblage.
ASCC treatment objectives for Second College Grant site	Single tree selection using Arbogast guidelines maintaining current forest composition: sugar maple > beech > yellow birch > red maple > red spruce > other Select for healthy and resistant individuals within current structure Maintain a continuous, multi-layered canopy Initiate a new cohort that reflects current overstory species composition Maintain current abundance of snags and downed dead wood (~1 snag/ac, 280 ft ³ /ac downed dead wood)	Group selection with gaps and reserves 0.1–0.25 acres Thinned matrix Sugar maple ≤ 30–40% of species composition, yellow birch, beech, red maple, red spruce, and other species together comprise 60–70% of stand composition Multiple combinations of species composition and structure present (multiple pathways to recovery from disturbance) Multiple age classes present (uneven-aged, ~5 cohorts) Increased amount of dead wood (snags: 1–3/acre; downed dead: >300 ft ³ /acre)	Continuous cover irregular shelterwood with gaps and reserves 0.25–1 acre Thinned matrix Dominance of future-adapted species currently onsite: yellow birch, red maple, beech Planted offsite climate-adapted species Change species composition while also increasing species richness (portfolio approach): 50% regeneration is future-adapted species already on site (n. hardwoods), 50% new species from off-site (slightly shifting away from strictly northern hardwoods) Uneven-aged, 20% of the area in regeneration (gaps) Create irregular vertical and horizontal structure, uneven-sized forest ecosystem, 50% canopy cover (50–60 ft ² /acre BA) across stand on average, 70–80 ft ² /acre BA in matrix

understanding the adaptive capacity conferred by adaptation treatments (D'Amato and Palik 2021, Messier et al. 2019). Analyses of forest structure and composition help quantify adaptive capacity for each treatment.

Four years after harvest, canopy tree species composition remains similar across the three treatments and control stands, indicating the challenge of attempting to shift species composition in a forest dominated by a small number of species using uneven-aged management techniques. Composition of regeneration shows more difference among treatments and reflects treatment goals of changing species dominance. The control stands and resistance treatment both show natural regeneration with the same composition as the overstory—sugar maple dominant, with considerable proportions of yellow birch and beech. Canopy gaps drive regeneration composition in the resilience and transition treatments. In these treatments, yellow birch and red maple seedlings are more abundant, and early successional species such as pin cherry and aspen also contribute notably to species diversity.² These patterns indicate that individual treatment components, such as gaps and reserves, will influence adaptive responses in different ways. Given that the silvicultural treatments have a limited ability to alter canopy tree composition, regeneration will likely drive changes in species composition, although changes will take a long time to become apparent in the canopy.

ADAPTATION PLANTINGS FOR TRANSITION

The pace of climate change exceeds that of historic tree migration, leading to the potential misalignment of species with future climate conditions (Janowiak et al. 2018, Sittaro et al. 2017, Zhu et al. 2012). The planting of species projected to be future climate-adapted (FCA) is an adaptive strategy that can support forest transition to new compositions (Pedlar et al. 2012, Williams and Dumroese 2013). Adaptation plantings may serve as critical sources for future populations, via population enrichment (augmentation of the pool of species onsite that may be FCA) or assisted range expansion (assisted migration of FCA species not onsite from adjacent climate zones). To test this, the SCG transition treatment included adaptation plantings of nine species (n = 4,675 seedlings) (Table 1). Species were selected using species distribution models (Janowiak et al. 2018, Peters 2020) and localized using regional manager and scientist knowledge with emphasis placed on species with similar functional traits relative to species on site forecasted to decline.

Over three growing seasons, 2,609 transplants survived (55.8 percent). Seedling growth and survival varied considerably across species. The primary biophysical drivers controlling seedling performance (survival/growth) were vegetative competition (-/-), seedling functional attributes (+/+), initial seedling size (+/-), and transfer distance inferred by population enrichment versus assisted range expansion (-/-). Vegetative competition played an important role with sites containing well developed natural regeneration more resistant to the introduction of adaptation plantings; however, heavily browsed sites diminished the strength of local vegetative competition and likely favored planted species that were less palatable. Notably, population enrichment species performed significantly better than assisted range expansion species, which exhibited more maladaptation (e.g., dieback, winter injury, reduced growth and survival), further highlighting the challenges of assisted migration.

Managers considering adaptation plantings may face additional challenges, namely extreme climate events (Park and Talbot 2018) and limited nursery capacity and infrastructure (Fargione

² Scientific names of tree species listed: yellow birch (*Betula alleghaniensis*); red maple (*Acer rubrum*); pin cherry (*Prunus pensylvanica*); aspen (*Populus* spp.); sugar maple (*Acer saccharum*).

et al. 2021). For example, the SCG planting trials experienced an extreme drought during planting and multiple late spring frost events with negative consequences on seedling performance that differed by species. Furthermore, securing a diverse suite of species and functional traits proved to be an additional hurdle because few regional nurseries offered FCA species that support a range of ecosystem services. In summary, although silvicultural responses to shifts in future species habitats may include adaptation plantings to facilitate FCA species establishment, the strength of local site competition and herbivory, functional traits, adaptation planting type, extreme climate, and the availability of quality and diverse nursery stock will be important for determining the efficacy of efforts to transition forest composition.

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Lessons from the Land: A New Approach to Use Site-Level Information to Guide Climate Adaptation

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INTRODUCTION

Foresters and other natural resource professionals are increasingly aware of the anticipated effects of climate change and adaptive management options at both the regional and local scale. Even as we gain more information about the potential impacts of climate change, however, there remain several challenges for translating large-scale and long-term climate change projections into practical action. Climate change projections and vulnerability assessments often deal with large spatial scales and general expectations. Forest managers are challenged to decide how best to apply this broad information at the stand level, where many forest management decisions are made. Among the many potential actions that could help adapt to climate change, some management actions may conflict with others, may not be applicable across forest cover types, or may not be applicable to a specific site.

In other professions, checklists are increasingly being used to manage complex procedures and decision-making (Gawande 2009). Checklists are constructed to help users apply knowledge and situational assessment consistently and correctly. Based on this model, we have created a Northern Hardwood Adaptation Checklist (checklist) tool to help filter the wide array of potential climate adaptation actions specifically for northern hardwood forests, and to help forest managers assess potential adaptation actions based on the conditions and potentials of a specific site. A session at the 2021 Northern Hardwood Conference introduced the initial version of the tool. Here, we explain how we created the Northern Hardwood Adaptation Checklist and offer some reflections on our lessons learned through the process.

CHECKLIST DEVELOPMENT

This checklist relies on a series of diagnostic questions to quickly assess key stand characteristics and potential climate change risks that might alter the course of management for a northern hardwood stand. For example, drought risk may be a critical climate change vulnerability for some northern hardwood stands, and forest managers can consider whether a particular site is vulnerable to this risk based on knowledge of a site's soils, aspect, and topographic features. Evaluating these site-level features can help a manager prioritize certain climate adaptation actions, such as emphasizing a higher proportion of drought-tolerant species when possible.

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We developed a preliminary list of diagnostic questions over an iterative process by reviewing information on projected climate change impacts to northern hardwood forests as well as existing silvicultural guidance. We intentionally considered the wide variety of site conditions that may exist in the northern hardwood cover type across Michigan, Wisconsin, or Minnesota. The list of 35 questions covers a range of stand characteristics that may influence climate vulnerability and adaptive capacity: ecological disruptions; access and operability; moisture and nutrients; diversity factors; and composition and stocking for the overstory, mid-story, and understory (Table 1). The questions are worded as succinct yes/no questions, where a “yes” answer indicates a potential risk factor in the stand. This format will assist forest managers to navigate the stand assessment quickly and consistently.

Additionally, the checklist contains an extensive list of climate change adaptation tactics for northern hardwood forests. We developed this list using the Menu of Adaptation Strategies and Approaches for Forest Management, from “Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers” (Swanston et al. 2016). We created specific tactics for northern hardwood management, and we organized these actions under the structure of broad “strategies” and more specific “approaches” from the menu. We gathered additional adaptation ideas for the checklist from existing ecological classification systems and northern hardwood management guides, such as the Minnesota Department of Natural Resources (DNR) native plant community classification system and silvicultural stand prescriptions, Kotar habitat classification system, and the Michigan and Wisconsin DNR silviculture guides (Burger and Kotar 2003, Kotar et al. 2002, Michigan DNR 2015, Minnesota DNR 2003, Minnesota DNR 2019, Wisconsin DNR 2017). The current version of the checklist contains 44 adaptation tactics ranging from ideas that span the full continuum of resistance, resilience, and transition options.

As users answer the diagnostic questions in the checklist, they are providing information about risk factors and site conditions as they exist in a given stand. For each question, we determined whether a yes or no answer would support or discourage the possible adaptation tactics. Most questions are relevant only to a few adaptation tactics, but multiple adaptation tactics can be influenced by a single answer or a combination of answers. As all 35 questions are answered, the tool tabulates a score for each adaptation tactic based on how often it is supported or discouraged. We coded these relationships into the tool based on our best understanding of the intent of potential adaptation tactics and the relevance of each adaptation tactic to different site-level conditions and risk factors.

The Northern Hardwood Adaptation Checklist is designed to help filter the list of potential adaptation actions into a more manageable list, but not to prescribe management actions or reduce flexibility. Therefore, the tool ultimately provides users with the entire list of potential adaptation actions, which are color-coded to indicate which actions are most consistent with the information provided. Users are still able to review the entire list of potential adaptation tactics and use their judgement about which actions to recommend for implementation. Adaptation actions are organized into general categories (e.g., tree planting and regeneration) to make it easier for users to review the list and evaluate the suitability of similar ideas.

We created additional steps in the checklist to allow users to provide information about the location and ownership of the stand, to enter specific management goals and objectives, and to review their stand’s risk factors prior to selecting adaptation actions. We modeled the structure and intent of the Adaptation Workbook (Swanston et al. 2016), a structured adaptation planning process developed by the Northern Institute of Applied Climate Science.

Table 1.—List of 35 diagnostic questions in the Northern Hardwood Adaptation Checklist, organized by general categories

General category	Diagnostic questions
Capacity for active management	Is the landowner willing to invest additional time and resources into management? (above and beyond a timber sale)
	Are a variety of timber markets available in this area? (for example, small diameter as well as large diameter markets)
	Is maximizing economic return the primary management goal for this stand? (for example, School Trust Land)
Ecological disruptions	Has the site previously been farmed or grazed? (confirmed site history or indications such as old fences)
	Does the site have evidence of high earthworm activity? (humus layer lacking)
	Does the site have evidence of high levels of deer browse?
	Are invasive species common throughout the site?
	Is interfering vegetation disrupting regeneration or other functions in the stand? (ironwood, hazel, Penn sedge, grasses, etc.)
	Does the site have serious current or looming forest health issues? (pests, diseases, etc.)
Access and operability	Do access or operability constraints limit the site's management to frozen ground conditions? (consider surface texture, drainage, impermeable soil layers, and landscape position)
	Would access to the site be impaired by a heavy rain event?
	Is the site south of the tension zone? (outside of Ecological Province 212)
Moisture and nutrients	Does the site have low nutrient availability? (refer to habitat type or NPC class or look for species in the understory that indicate nutrient-poor sites)
	Does the site have coarse-textured or drought-prone soils? (refer to habitat type or NPC class or look for species in the understory that indicate drier sites)
	Does the site's landscape position increase the risk of drought? (south-facing aspect, depth to bedrock, quirks of the prevailing weather pattern, etc.)
	Does the site's landscape position reduce the risk of drought? (toe of a slope, north-facing aspect, springs and seeps, lake effect snow belt)
Composition and stocking - overstory (trees greater than 5 inches d.b.h.)	Is the overstory dominated by a single species such as sugar maple? (more than 70% of the basal area [BA])
	Is the overstory primarily composed of species expected to decline due to climate change or other factors over the next 50 years?
	Are there significant quality concerns in the overstory? (frost cracks, damage, poor form, other defects)
	Is the overstory understocked?
	Is the site overstocked such that growth is being suppressed or there is an elevated drought risk?
Composition and stocking - mid-story (trees 1 to 5 inches d.b.h.)	Is the mid-story less diverse than desired?
	Is the mid-story primarily composed of species expected to decline due to climate change or other factors over the next 50 years?
	Are there significant quality concerns in the mid-story? (frost cracks, damage, poor form, other defects)
	Do mid-story trees have less vigor than large overstory trees? (For example, do small trees have a smaller live crown ratio than large trees?)
	Does the mid-story have below expected or unacceptable stocking?
Composition and stocking - understory (trees less than 1 inch d.b.h.)	Is the regeneration layer less diverse than desired?
	Is the regeneration layer primarily composed of species expected to decline due to climate change or other factors over the next 50 years?
	Is there inadequate regeneration to perpetuate the stand?
Diversity factors	Do vernal pools or other sensitive sites occur on the site?
	Are Canada yew, orchids, or other special species present?
	Is there a high proportion of oak in the stand? (30 BA of oak, well distributed within the stand)
	Does the stand contain oaks or other species anticipated to fare well under future climate conditions?
	Is the site lacking large standing or down dead trees (nurse logs)? (at least 3/ acre greater than 12 inches in diameter, at least 6 feet long)
	Is stand density uniform throughout the site?

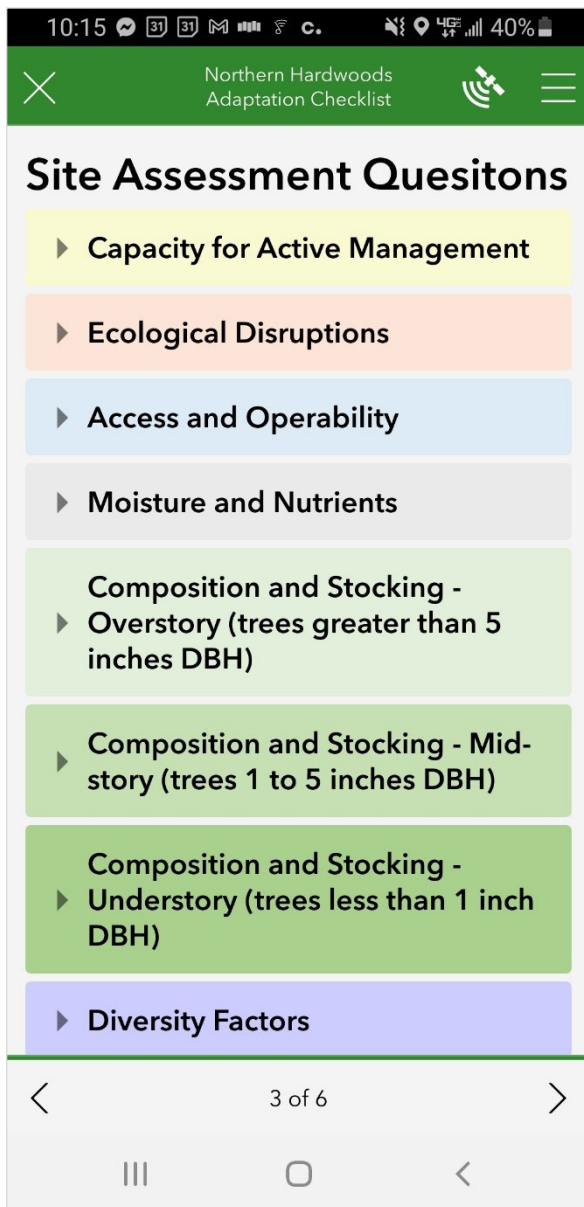


Figure 1.—A screenshot of the Northern Hardwood Adaptation Checklist, displayed on a smartphone within the Survey123 platform.

We created an initial version of the Northern Hardwood Adaptation Checklist in Survey123 to allow many users to access the tool from a phone, tablet, or desktop, even without internet access (Fig. 1). Survey123 is a program developed by ESRI (Redlands, CA) to create, share, and analyze surveys (<https://survey123.arcgis.com/>). Readers can contact author Stephen Handler for instructions to download the checklist using Survey123.

LESSONS LEARNED

We are pleased that the initial version of the Northern Hardwood Adaptation Checklist provides a simple and consistent way for foresters to consider how site-level conditions may affect the range of climate adaptation actions that could be implemented in a stand. We were able to consolidate a large amount of information into a streamlined process and make useful connections between risk factors and related management tactics for climate change adaptation.

Although northern hardwood is a common forest type across the Lake States region, the site-level conditions across these states vary substantially. It was challenging to write diagnostic questions that would apply to such diverse conditions. We also had to consider the tradeoff between asking dozens of questions to better identify the features of a stand and needing to constrain the tool to a manageable list of questions that could be completed swiftly. From our shared experiences, we learned that even within a state there are regions and sites that have unique characteristics that might not be adequately assessed by our questions.

This process also reinforced the idea that a variety of adaptation actions can be available to address a particular condition, resulting in a tool that is more of a menu of possibilities and not a prescriptive outcome. Therefore, coding the checklist to associate yes/no responses for specific questions with an array of potential adaptation actions can be a matter of interpretation. It will be necessary to thoroughly test this tool across a diversity of stand conditions and management contexts to ensure that the checklist is filtering the list of adaptation tactics consistently.

Similarly, constructing this tool forced us to think creatively about the variety of adaptation tactics that could be employed in a northern hardwood stand. User feedback will be helpful to generate additional ideas as we continue to test the tool. As we refine the diagnostic questions and adaptation tactics, it will be important to clearly document the rationale for associating adaptation tactics with particular questions, recognizing that the justification may be a combination of published literature and manager input.

The Northern Hardwood Adaptation Checklist is only on the starting block for testing and improvement. We used it on a small sample of sites representing some of the vast variability across the Lake States. Testing the Survey123 platform with the audience at the 2021 Northern Hardwood Conference is only the first step in future modifications and full deployment of the tool. Further review by additional researchers and managers will be critical. This version with a northern hardwood focus is the “proof of concept,” and this idea could be applied to other forest types in the future.

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We are grateful to Lucas Spaete (Minnesota DNR) for explaining the capabilities of the Survey123 platform and for coding the current version of the Northern Hardwood Adaptation Checklist. John Kotar (University of Wisconsin-Madison, retired) joined our initial project discussions and explained the habitat classification system. Chris Swanston, Maria Janowiak (USDA Forest Service and Northern Institute of Applied Climate Science), and Todd Ontl (Michigan Technological University and Northern Institute of Applied Climate Science) provided critical feedback on early versions of the tool. Maria Janowiak also reviewed this manuscript and provided many helpful suggestions.

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Genetic Considerations for Assisted Migration Efforts: Northern Hardwoods

Carolyn C. Pike¹

EXTENDED ABSTRACT

Forest managers historically sought locally sourced seed for planting to ensure that future forests were adapted to local conditions. As the climate warms, managers are increasingly seeking seed from more southerly locales. This movement of seed from outside the local seed zone, known as assisted migration, is one of several silvicultural tools being enacted to improve the resilience and adaptation of forests in the future (Williams and Dumroese 2016). A variety of strategies to implement assisted migration have been proposed (Breed et al. 2013, Havens et al. 2015, Potter and Hargrove 2012, Vitt et al. 2010). Genetic considerations can help inform which strategy is most likely to succeed, but resources for northern hardwood trees are scarce. The objective of this presentation is to update managers on existing knowledge from genetics studies related to northern hardwood trees. Secondly, I will describe how to incorporate the Seedlot Selection Tool and the new eastern seed zones (Pike et al. 2020) into an assisted migration plan.

Four genetic considerations should be considered before assisted migration is undertaken: knowledge of safe seed transfer distances, risks of outbreeding depression, potential to enhance insect/disease outbreaks, and risks of hybridization. The effects of long- and short-distance seed transfer have been extensively studied in progeny and provenance trials established across North America in the 20th century as part of an organized tree improvement effort on commercially valuable conifers. Information on the genetics of most northern hardwood species and other noncommercial species is largely deficient. Provenance trials that were established for northern red oak (*Quercus rubra* L.), yellow birch (*Betula alleghaniensis* Britton), and sugar maple (*Acer saccharum* Marsh.) are being reassessed to help inform assisted migration efforts (Leites et al. 2019). These studies have limited inference space because few gardens were planted and most are located within the central portion of the species ranges; extreme sites, and therefore extreme transfer events, were not tested. Transfer distances of 100 to 200 miles (from south to north) are well tolerated by jack pine (*Pinus banksiana* Lamb.) (Thomson and Parker 2008), a species with conservative transfer recommendations. In the absence of empirical data, a conservative approach (100 to 200 miles) is likely to be well tolerated by most northern hardwoods.

Studies of population genetics assess genetic diversity on neutral (noncoding) DNA are useful to quantify the historical migration and inbreeding for a species. These studies have revealed that most tree species are highly heterozygous owing to the extensive movement of seeds and pollen across the landscape (Hamrick et al. 1992). The genetics of several hardwood species have been studied, including sugar maple, yellow birch, and red maple (*Acer rubrum*). These northern hardwood trees have high levels of genetic variation and high gene flow (Thomson et al. 2015) in some cases at levels comparable to conifers (Jones et al. 2006). This latent heterozygosity implies that outbreeding depression is not a likely consequence from assisted migration of northern hardwood trees. Small-statured native plants, with limited seed dispersal, are more likely to experience outbreeding depression (Jones et al. 2006) and should be moved with caution.

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Many hardwood tree species are capable of interspecific hybridization which is often undetected because offspring from a hybrid cross may resemble either parent (Crystal et al. 2016). For example, northern red oak (*Quercus rubra*) readily hybridizes with other species in the red oak (Lobatae) group (Aldrich et al. 2003); yellow birch and paper birch (*Betula papyrifera* Marshall) hybridize in the Lake States (Barnes et al. 1974, Thomson et al. 2015); and butternut (*Juglans cinerea* L.) frequently hybridizes with Japanese walnut (*Juglans ailantifolia* Carrière) (Hoban et al. 2009). Seed sources with a hybrid pedigree, that result from a cross between species with diverse cold tolerances, may lack sufficient hardiness when transferred northward, although no studies have confirmed this outcome. For example, managers in Wisconsin who acquire seed from Indiana may inadvertently acquire seed with a hybrid pedigree that includes the more southerly shumard oak (*Q. shumardii* Buckley). These hybrid seeds may lack the cold tolerance needed to survive in the upper Great Lakes, but managers have few options other than to weed out seedlings that are poorly adapted or to identify seed sources with lower rates of hybridization.

Assisted migration may exacerbate existing pest or pathogen complexes especially if trees are planted outside their existing range in a range-expansion effort. For example, the movement of northern red oak to northern climates, where red oak is uncommon or absent, may inadvertently introduce eastern gall rust (*Cronartium quercuum* (Berk.) Miyabe ex Shirai), a major pest on jack pine that requires oak as an alternate host (Anderson 1970). In general, moving southern seed sources to northern locales within the existing range is a safer recommendation than range expansion. Future studies that quantify the interactions of pests and pathogens with translocated seed sources are needed to inform managers of potential risks (King 1971). Studies are also needed to better understand phenology (Lu and Man 2011), inherent physiological differences of novel seed sources (Bansal et al. 2015), and other ecological constraints (Winder et al. 2011) that result from seed movement. Northern hardwood trees, in general, should be resilient to the effects of assisted migration because of their inherent genetic diversity and life history traits that promote high gene flow. New seed transfer guidelines, which include a summary of genetic considerations, are being developed for publication in the near future.

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Tree Assisted Migration in a Browsed Landscape: Developing an Assessment of Susceptibility

Emilie Champagne, Alejandro A. Royo, Jean-Pierre Tremblay, and Patricia Raymond¹

Abstract.—Assisted migration is a promising silvicultural tool that could promote the sustainability of forest ecosystems and ecological services in the context of climate change. Assisted migration plantations, however, could be at a high risk of failure when mammalian herbivores (e.g., deer and hares) are abundant. Here, we developed an approach based on chemical content to predict the susceptibility to browsing of translocated seedlings. First, we determined which chemical compounds would be appropriate proxies of susceptibility. Second, we analyzed the chemical content of eight North American species selected for an assisted migration plantation and determined the relative susceptibility to herbivores of species and geographic provenances within species. We compared the ranking to browsing reported in the literature. For six species out of eight, our susceptibility rankings were congruent with information available in the literature. With this study, we provide a tool that could guide managers in species and provenance choices for assisted migration when contending with a high risk of browsing.

CONTEXT

Forest managers are considering several adaptation tools to promote the sustainability of forest ecosystems and maintain their ecological services to human populations in the context of climate change. One of these tools, assisted migration, consists of displacing tree species and/or populations to locations with suitable future climate conditions (Pedlar et al. 2012). Assisted migration planting could take various forms, such as single-species enrichment planting under partial forest cover or multi-species plantations in open conditions. The objectives are increasing forest resilience to climate-related disturbances (e.g., drought, insect outbreaks) and contributing to the maintenance of ecosystem services and productivity (Ste-Marie et al. 2011). Assisted migration plantations, however, could fail to produce viable forests under high herbivory pressure from mammalian herbivores. Browsing by cervids (e.g., white-tailed deer, *Odocoileus virginianus*; moose, *Alces americanus*) and leporids (e.g., snowshoe hares, *Lepus americanus*) can reduce the growth and survival of planted seedlings, and consequently these herbivores have a lasting effect on forest recruitment and stand composition. Seedlings produced in nurseries could be more attractive to herbivores than natural regeneration because of the favourable growth conditions and resulting higher nutrient content of these seedlings (McArthur et al. 2003). Additionally, translocated species or populations might lack the defenses against those herbivores and could thus be more attractive than native species and/or local genotypes (Averill et al. 2016, Levine et al. 2004). Assisted migration is a high investment silvicultural measure, and as such, potential risk factors such as browsing should be evaluated and minimized to favour its success.

Browsing by mammals can be reduced through wildlife management aimed at regulating herbivore densities and using physical protection (e.g., fence, tree shelters). While these actions can be effective, they require considerable resources to implement, monitor and maintain (Redick and Jacobs 2020). On the other hand, forest managers could minimize the risk of browsing before planting by selecting species and genotypes with low susceptibility to herbivores. In

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this study, we developed an approach to predict susceptibility to mammalian herbivores, using seedlings' chemical content, which is an indicator of phytochemical defense and nutritive value to herbivores. First, we evaluated which chemical analyses could provide adequate proxies of susceptibility to herbivores (Champagne et al. 2020). Second, we compared the potential susceptibility to browsing of eight eastern North American species used in an assisted migration plantation (Champagne et al. 2021). To assess the reliability of our approach, we compared susceptibility ranking realized with chemical analyses to a systematic review of mammalian browsing throughout the geographic range of these tree species.

CHEMICAL ACTORS OF SUSCEPTIBILITY

Among the wide variety of chemicals produced by plants, some are linked to defense against herbivores and pathogens. Several groups of chemicals are especially recognized for their deterring, antinutritive, or toxic effects to herbivores, but there are some uncertainties regarding which compounds are efficient against cervids and leporids (DeGabriel et al. 2014). We conducted a systematic review of the literature about the relationship between plants chemical compounds and selection by these herbivores (Champagne et al. 2020). We evaluated 133 articles, covering 50 years of research, 18 species of cervids and leporids, and four continents. Based on this review, we determined that terpenes (a group of compounds particularly abundant in conifers) and specific groups of phenolic compounds (e.g., flavonoids) could be good proxies of susceptibility to browsing, especially to compare species. High concentration in those compounds would be linked to a lower susceptibility to browsing. Additionally, fiber analyses (e.g., cellulose and lignin) and total phenolic compounds could be used for comparing susceptibility among populations of the same species. Again, high concentration in fiber and phenolic compounds would be linked to low susceptibility.

POTENTIAL SUSCEPTIBILITY AS EVALUATED BY CHEMICAL COMPOSITION

We created chemical profiles for the winter shoots of eight North American tree species using two nutritive elements (total nitrogen and cellulose) and four groups of compounds linked to susceptibility (Champagne et al. 2021): lignin, total phenolic compounds, flavonoids and, for conifers, total terpenes. The species were selected for an experimental assisted migration plantation, based on their economic value and ecological functions in the mixed forest (balsam fir-yellow birch bioclimatic domain of Québec; Saucier et al. 2009). Six of the species are currently present in these forests (*Acer saccharum* Marsh., *Picea glauca* (Moench) Voss, *Picea rubens* Sarg., *Pinus strobus* L., *Pinus resinosa* Aiton, and *Thuja occidentalis* L.), although the projected climate could be unfavourable for both *Picea* species and *T. occidentalis* (Périé et al. 2014). These predicted climate conditions, however, could be favourable for the remaining species, *Quercus rubra* and *Prunus serotina*. Seedlings of each species were produced in a single nursery (provincial government nursery in Berthierville; Fig. 1), with seeds from geographic provenances representing three climate analogues (i.e., locations where the current climate is similar to the anticipated climate of another location, here the plantation site). One geographic provenance had a climate similar to the current plantation site climate (approximately Québec City region). The other two geographic provenances represented the climate predicted at the plantation site for the mid-century and end of the century (southern Québec, and northeastern USA and Nova Scotia, respectively). To create the chemical profiles, we sampled seedlings from the batch produced for planting, but that were never planted.



Figure 1.—Left: Seedlings to be planted at the experimental assisted migration site (Réserve faunique de Portneuf, QC, Canada). Seedlings used for the assessment of their potential susceptibility to herbivores were selected among these. Courtesy photo by Patricia Raymond, used with permission. Right: Example of white-tailed deer (*Odocoileus virginianus*) browsing on *Pinus strobus* at the plantation site. Courtesy photo by Emilie Champagne, used with permission.

Table 1.—Potential susceptibility to browsing ranking based on chemical profiles. The profiles of species at the same level were not statistically different.

	Species
Low susceptibility ↓	<i>Picea glauca</i> and <i>Picea rubens</i>
	<i>Pinus strobus</i> and <i>Thuja occidentalis</i> ^a
	<i>Pinus resinosa</i>
	<i>Prunus serotina</i>
	<i>Quercus rubra</i>
High susceptibility	<i>Acer saccharum</i>

^a For these species, the systematic review of browsing across the species range indicates a higher browsing frequency and intensity than predicted based on chemical profiles.

We used multivariate statistical analyses (principal component analyses) to rank species and population within species from the most to the least susceptible. Based on this classification (Table 1), conifers were deemed less susceptible than broadleaf species, although variation in susceptibility was statistically significant inside those groups. These results were congruent with browsing reported in the literature for six of the eight species. For example, *Picea* species had the lowest potential susceptibility based on the chemical composition of the species set and the literature supports a low occurrence and intensity of browsing on these species. At the other end of our ranking, the species ranked potentially more susceptible (i.e., *Quercus rubra* and *Acer saccharum*) were reported to be frequently browsed at moderate to high intensity. There are also several reports in the literature of negative effect of browsing on the growth, survival, and abundance of these species. We underestimated, however, the susceptibility of *Pinus strobus* and *Thuja occidentalis*, which are frequently browsed by specific herbivores (small mammals and white-tailed deer, respectively). These results highlight the importance of considering the type of herbivore present when evaluating the potential risks for translocated seedlings. We also identified differences in chemical profiles among geographic provenances that could be linked to susceptibility for *Picea rubens*, *Pinus resinosa*, *Prunus serotina*, and *Thuja occidentalis*. The monitoring of the experimental assisted migration will allow us to determine if these differences

are reflected in the cumulative browsing rate on the seedlings at the plantation site. It will also allow us to consider how tolerance, i.e., the ability to regrow following browsing, could mitigate the negative effects of browsing on susceptible planted seedlings.

CONCLUSION

We propose to use chemical profiling approach summarized here as a preliminary screening tool to identify species more resistant to mammalian herbivores. The chemical profiles could be extended to other herbivores and pathogens, using additional appropriate chemical analyses. Our approach, based on the objective assessment of multivariate analyses results, could be replicated to compare the potential susceptibility of other species considered in adaptation to climate change scenarios. It could be especially useful when contending with novel plant-herbivore relationships, such as forestry and conservation-assisted migration or species invasion.

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***Quercus rubra* Seedling Biomass Response Related to Mean Annual Temperature Conditions of Associated Provenance**

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Abstract.—*Quercus rubra* L. is a hardwood species found throughout the eastern United States. Although climate change is projected to increase this species' suitable habitat range, current population structures and migration patterns may not be suitable to sustain future forest health. To investigate how populations respond when planted outside of their traditional ranges, we collected seeds from 22 *Q. rubra* populations spanning the species range and planted them in two common garden sites. Ford forest (cooler and drier) and Kellogg Forest (warmer and wetter) sites are located in Michigan's upper and lower peninsulas, respectively. During the 2019 and 2020 growing seasons, *Q. rubra* biomass increased with increasing seed source mean annual temperature (MAT), with a steeper slope at Ford in 2020. We also observed more frost damage at the Ford site in plants that evolved with a higher MAT.

INTRODUCTION

Quercus rubra L. (common name: northern red oak) is a hardwood tree commonly found within forested ecosystems of eastern North America (Little 1971). Climate change not only increases annual temperature averages, it also restructures ecosystems norms (Frelich and Reich 2010, Seddon 2010). For many forest species, suitable habitat is expected to decline because of climate change. However, within eastern North America, an opposite trend is generally projected for many oak species including *Q. rubra*. According to suitable habitat modeling, such as DISTRIB-II and the Parallel Climate modeling, the range of *Q. rubra* is expected to increase by 51 percent and 50 percent under high (4.8 °C increase by 2100) and low (2.6 °C increase by 2100) climate change scenarios, respectively (Collins et al. 2013, Iverson et al. 2008, Peters et al. 2019).

Projected increases in suitable habitat for *Q. rubra* should not be mistaken for climate change readiness. Since the species range is quite expansive, current *Q. rubra* provenances have many distinctive localized adaptations suited for the present/past climate conditions. And although intraspecific gene flow between oak populations may well be maintained through wind pollination, loss of stand density and forest fragmentation pose threats to oaks, including for *Q. rubra* (Fernández and Sork 2007, Gerwein and Kesseli 2006, Oyama et al. 2017). Without human intervention, population health within northern *Q. rubra* provenances may depreciate, posing a real threat to future forests.

Forestry assisted migration is a tool used to prevent species loss or forest fragmentation and increase a species' climate-change adaptive potential. This assisted migration practice includes the movement of populations within current species ranges and into populations located in the leading-edge habitat, i.e., range expansion (Pedlar et al. 2012, Ste-Marie et al. 2011). Because of forestry assisted-migration's specific aims, the risk for introduction of invasive species, diseases, or

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Table 1.—Site locations and seed source mean annual temperature (MAT) specific to *Q. rubra* provenances planted at the Ford and Kellogg common gardens. Provenances are listed based on seed source MAT, highest to lowest. GPS coordinates are listed as latitude, longitude.

Population Name, State	Population ID	GPS	Families (#)	Seed source MAT (°C)
Eagle Mine, MI	13	46.749, -87.891	6	4.1
Dow forest, MI	1	47.425, -88.056	4	4.2
Cliff Drive, MI	3	47.354, -88.350	4	4.3
Baraga Plains, MI	11	46.673, -88.529	3	4.4
Copper Harbor Sand dunes, MI	2	47.440, -88.219	6	4.5
Russell, WI	23	46.768, -91.105	3	4.6
Maasto Hiihto (1), MI	4	47.138, -88.610	6	4.9
Nara Trails (1), MI	5	47.103, -88.520	2	4.9
Nara Trails (2), MI	6	47.107, -88.551	6	4.9
Nara Trails (3), MI	7	47.105, -88.529	5	4.9
Nara Trails (4), MI	8	47.102, -88.554	5	4.9
Nara Trails (5), MI	9	47.106, -88.555	5	4.9
Maasto Hiihto (2), MI	30	47.140, -88.612	3	4.9
Blue Berry Ridge Trails, MI	14	46.456, -87.424	6	5.0
Mouth of the Huron River, MI	12	46.909, -88.036	6	5.4
Au Train, MI	15	46.438, -86.878	6	5.4
Big Bay de Noc, MI	16	45.868, -86.518	3	5.5
Cygnet, OH	28	41.238, -83.680	5	9.8
Warfordsberg, PA	27	39.737, -78.180	4	11.3
Hoosier, IN	18	38.060, -86.661	4	12.9
Trail of Tears, IN	21	37.480, -89.360	6	13.6
Rockwood Park, VA	29	37.451, -77.580	4	14.2

novel hybridizations is minimal (Pedlar et al. 2012, Ste-Marie et al. 2011). The populations selected for movement, should be selected based on their potential for handling a site's future climate (Jump and Peñuelas 2005, Krutovsky et al. 2012, Mátyás 2010). Provenance experiments can be used to categorize a population's phenotypic plasticity and environmental tolerance (Etterson et al., 2020, González-Martínez et al. 2006, Pedlar et al. 2012). In the case of the northern red oak, provenance studies often observed that seed stock from southern provenances are better adapted to changing climate in northern latitudes (Etterson et al. 2020, Kriebel 1976). To paraphrase Clark and Schlarbaum (2018), the best way to ensure the health of *Q. rubra* population is by planting a diverse stock of tree gathered from many populations.

To gain a better understanding of the *Q. rubra* populations' specific environmental tolerance, we designed two common garden sites that house 22 unique populations (Table 1). Biometric traits of all trees are routinely collected at these sites. Here we present the preliminary results relating to 2019 and 2020 biomass measurements and 2021 frost damage. We hypothesized that the response of each *Q. rubra* population to environmental site conditions would be largely dependent on a populations' seed-source climate variables.

METHODS

***Quercus rubra* Seed Collection and Germination**

Quercus rubra inhabits forests spanning from southern Quebec and Ontario (Canada) to northern Louisiana (USA) and from the Mississippi River to the east coast of North America (Little 1971). Within this range, we collected seed stock from 22 distinctive populations (Table 1). Within each population, seeds were collected from multiple families. Approximately 50 acorns were directly sampled from the branches and immediate area surrounding the family's mother tree. Because *Q. rubra* is wind pollinated, all seeds collected from a single mother tree are half-siblings. After collection, the seeds were stored at 4 °C between 3 to 6 months for stratification (Bonner 2008).

After stratification, 20 seeds that passed the float/sink test from each family were randomly selected for germination at the Michigan Technological University College of Forest Resources and Environmental Sciences greenhouse. The acorns were individually planted into half-liter plugs filled with a soil/sand mix (75/25 percent) on April 3 and 4, 2019. Greenhouse conditions were maintained at 16-hour light and 8-hour dark periods. Day and night temperatures were maintained at 23 °C and 18 °C, respectively. Each of the half-liter plugs were saturated with water every 3 days. This period of greenhouse growth lasted approximately 3 months.

Common Garden Site Description and Design

Common garden sites are located at the Michigan State University W.K. Kellogg Experimental Forest (Augusta, MI; 42.47 N, -85.36 W) and the Michigan Technological University Ford Forest (Alberta, MI; 46.64 N, -88.48 W). The Kellogg site is considerably warmer and wetter than the Ford site. The mean annual temperatures are 9.9 °C and 4.9 °C, respectively; and yearly precipitation are 1027 mm and 879 mm, respectively. Site soil type is coarse sandy loam and loam, respectively (NRCS 2021).

The Kellogg and Ford common garden sites were established June 12 and June 19, 2019, respectively. At each common garden, 810 experimental red oak seedlings were arranged in rows with spacing of 1.5 m × 0.76 m. Each common garden site contains 27 blocks, consisting of 30 seedlings planted in 3 rows with 10 plants per row. The borders of each block are separated by buffer trees. Seedling locations were set using a semi-randomized block design (Dodge 2008). Each block contains at least one plant per population.

To prevent deer browsing, the perimeter of the common gardens is surrounded by 3 m high fences. To reduce the impacts of resource competition on the seedlings (e.g., light and nutrients), we employed regular weed management including lawn mowing, hand weeding, and herbicidal treatment, as needed. Plants at the Ford site were watered as necessary during the 2019 and 2020 growing seasons when dry conditions endangered seedling survival. To support root nutrient uptake, iron chelate was administered to all trees at the Ford common garden on August 12, 2019, and June 13, 2020.

Biometric Trait Assessment

Biometric traits were measured for all experimental plants in the common gardens. The biometric traits measured included seedling height (H), crown diameter (CD) measured in two directions, and stem diameter (SD). H measured the distance from a seedling's stem base to the terminal shoot tip, to the nearest centimeter. CD measured the distance from one side of the crown

through the central axis, to the nearest centimeter. To account for the lack of uniformity in crown growth, each seedling's CD was recorded for both horizontal and perpendicular directions (in reference to the rows and columns). SD was measured at the seedling root collar using calipers to 1/100 millimeter. Using these measurements, we calculated an aboveground biomass index (BI) for each seedling using the following formula:

$$BI = \left(\frac{H * CD1 * CD2}{3} * SD \right) * 1/1000$$

As an index, the BI is a unitless measurement meant to provide a way of comparing the seedlings.

Greenhouse measurements were used to approximate an initial BI measurement (BI-0) for the seedlings. The term “approximate” is used here because stem diameter measurements were not collected within this dataset as this could potentially damage the seedlings at this stage. All stem diameters are set at 1 mm, a value that is less than the smallest measurement in the first set of field measurements. To determine seedling growth between the common garden planting date and the end of the 2019 growing season, BI-0 values have been subtracted from the 2019 end-of-season BI (BI-2019). Similarly, the sum of BI-0 and BI-2019 were subtracted from the 2020 end-of-season BI to determine the BI-2020. The Ford site biometric trait data shown here was collected on August 27, 2019, and August 28, 2020. The Kellogg site biometric trait data shown here was collected on August 20, 2019, and August 13, 2020.

Frost Damage Assessment

In late May 2021, seedlings at the Ford site experienced multiple days of temperatures at or below freezing. At this time, most of the seedlings had gone through bud burst. We assessed the extent of frost damage through an index. Severity of frost damage was assigned a value between 0 and 3, where “0” indicated no frost damage and “3” indicated severe frost damage. The percentage of the seedlings that were afflicted with frost damage was assessed (approximated to be 0, 10, 25, 50, 75, 100 percent). The frost damage index was the product of severity and percentage. These data were collected on May 31 and June 1, 2020. Dormant seedlings were excluded from this analysis.

Statistical Analysis

A one-way ANCOVA was performed to determine if the common garden sites (Kellogg and Ford), seed source mean annual temperature (MAT), and site-MAT interaction had significant statistical effects on BI during the 2019 and 2020 growing seasons (i.e., $BI \sim MAT * Site$). Whisker boxplots of BI (2019 and 2020) by population were made to understand a population's BI distribution. A linear regression analysis was performed to determine if MAT had a significant effect on *Q. rubra* BI during the 2019 and 2020 growing seasons. Seedlings without leaves were excluded from these analyses since they could not be accurately assessed using our BI formula.

Since frost damage was only categorized at our Ford common garden site, we performed a linear regression to determine if MAT had significant effect on *Q. rubra* frost damage in 2021. Whisker boxplots of the frost damage index by population were made to compare data distribution for each population. Dormant seedlings were excluded from this analysis.

RESULTS

Seed Source Mean Annual Temperature and Site have a Significant Effect on *Quercus rubra* Seedling Above Ground Biomass Index

In both 2019 and 2020 growing seasons, we observed significant effects of seed source MAT and common garden site on *Q. rubra* aboveground biomass index. The average biomass index for *Q. rubra* populations was greater at the Ford common garden site in 2019. A similar trend was observed during the 2020 growing season (Table 2, Fig. 1). Although no interactive effect between seed source MAT and common garden site was observed in 2019, we did observe an interactive effect in 2020 (Table 2).

Table 2.—Effects of seed source mean annual temperature and site on *Q. rubra* biomass production and frost damage. One-way ANCOVA used for BI 2019 and BI 2020 data, and linear regression for FD 2021 data (for Ford common garden only). Statistically significant p-values are in bold. BI: biomass index; DF: degrees of freedom; FD: frost damage; MAT: seed source mean annual temperature.

Source	BI 2019		BI 2020		FD 2021	
	DFn/DFd	p	DFn/DFd	p	DFn/DFd	p
MAT	1/1086	<0.001	1/1006	<0.001	1/614	<0.001
Site	1/1086	<0.001	1/1006	<0.001	NA	NA
MAT*Site	1/1086	0.576	1/1006	0.011	NA	NA

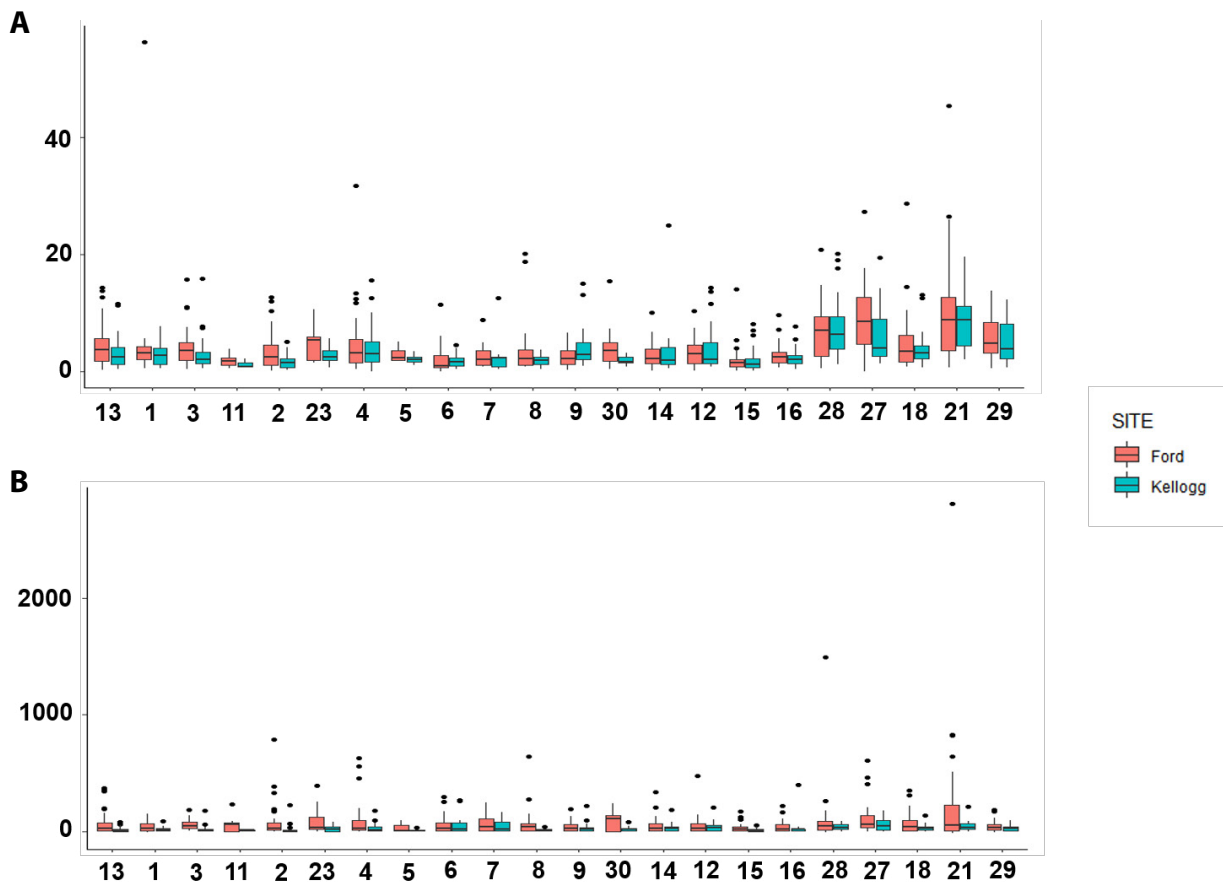


Figure 1.—Biomass indexes for *Q. rubra* provenances. Provenances are ordered based on seed source MAT, from lowest to highest. Ford site boxplots are red; Kellogg site boxplots are blue. (A) 2019 biomass indexes, and (B) 2020 biomass indexes.

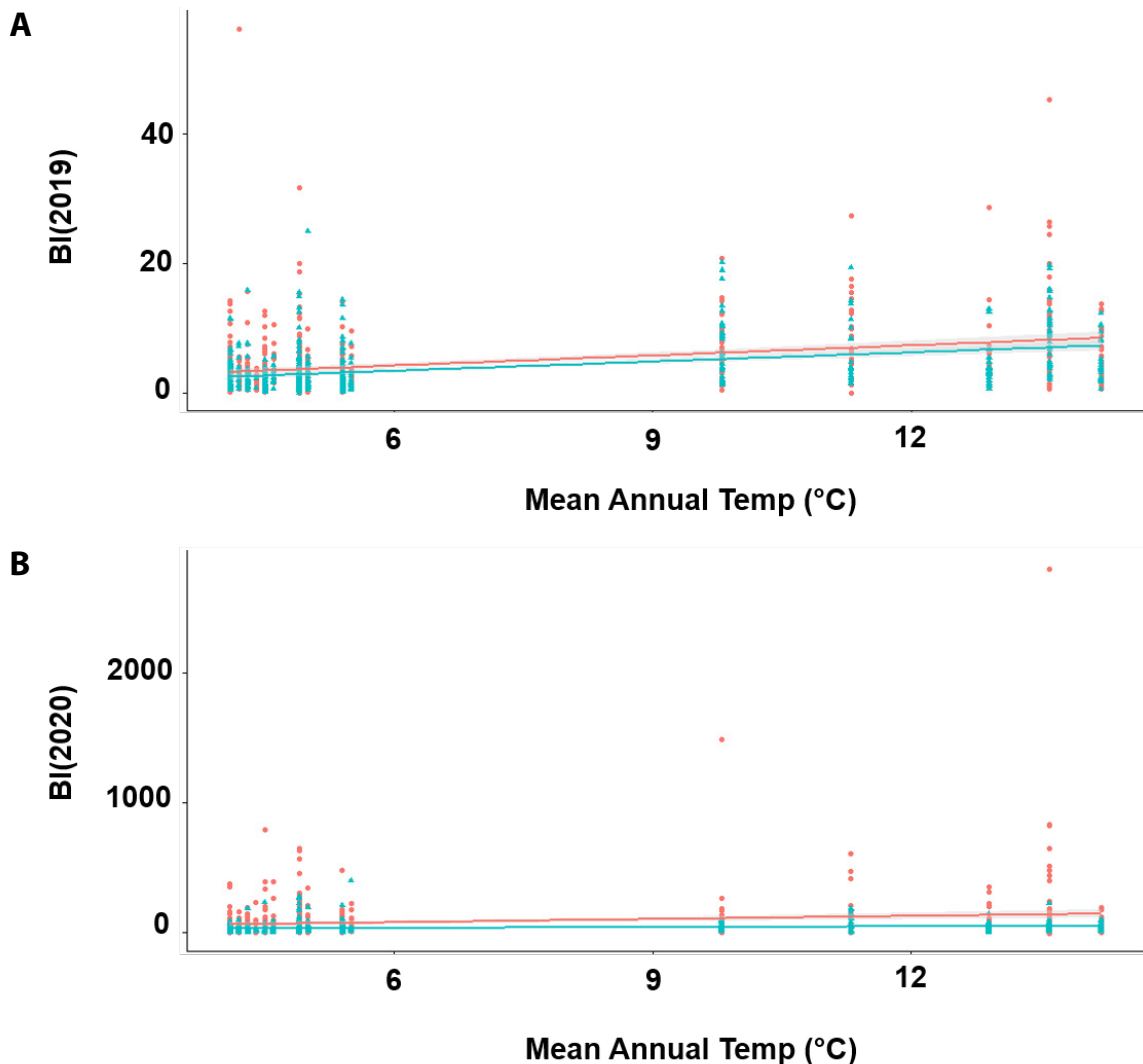


Figure 2.—Positive correlations observed for linear regressions of *Q. rubra* biomass index (BI) with respect to seed source mean annual temperature (MAT). Ford site data are orange circles; Kellogg site data are teal triangles. (A) 2019 biomass indexes with respect to MAT: Ford site β_0 , β_1 , R^2 , and p-values are 1.037 BI, 0.388 BI/°C, 0.078, and <0.001, respectively. (B) Kellogg site β_0 , β_1 , R^2 , p-values are 0.570 BI and 0.327 BI/°C, 0.114, and <0.001, respectively. 2020 biomass indexes with respect to MAT (B): Ford site β_0 , β_1 , R^2 , and p-values are 25.672 BI, 8.151 BI/°C, 0.026, and <0.001, respectively; Kellogg site β_0 , β_1 , R^2 , and p-values are 18.814 BI and 1.979 BI/°C, 0.024, and <0.001 respectively.

We observed a strong, positive correlation between *Q. rubra* aboveground biomass and seed source MAT at both common garden sites during 2019 and 2020. Similar linear regression equations describe correlation between MAT and BI at both the Kellogg ($Y = 0.327\text{BI}/\text{MAT} * X + 0.570\text{BI}$) and the Ford ($Y = 0.388\text{BI}/\text{MAT} * X + 1.037\text{BI}$). In 2020, we found the slope of the Ford site regression line to be more than four times greater than that of the Kellogg site regression. The linear regression equations $Y = 8.151\text{BI}/\text{MAT} * X + 25.672\text{BI}$, and $Y = 1.979 * X + 18.813\text{BI}$, respectively, describe the trends observed at the Ford and Kellogg sites (Fig. 2). Low R^2 values were found for each regression analysis, demonstrating that MAT only explains some of the variability of the biomass index means. Significant p-values were found for each of the linear regressions, demonstrating that MAT has a significant effect on biomass production at both common garden sites (Fig. 2).

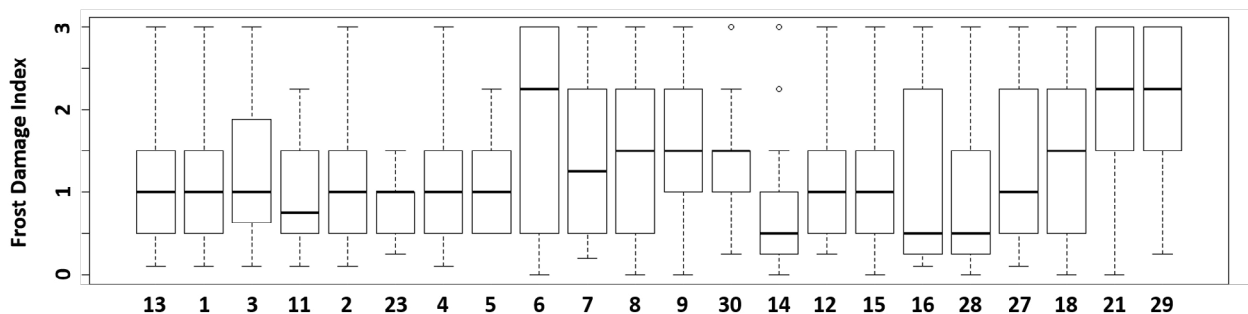


Figure 3.—2021 frost damage index boxplots for *Q. rubra* provenances at the Ford common garden. Provenances are ordered based on seed source mean annual temperature, from lowest to highest.

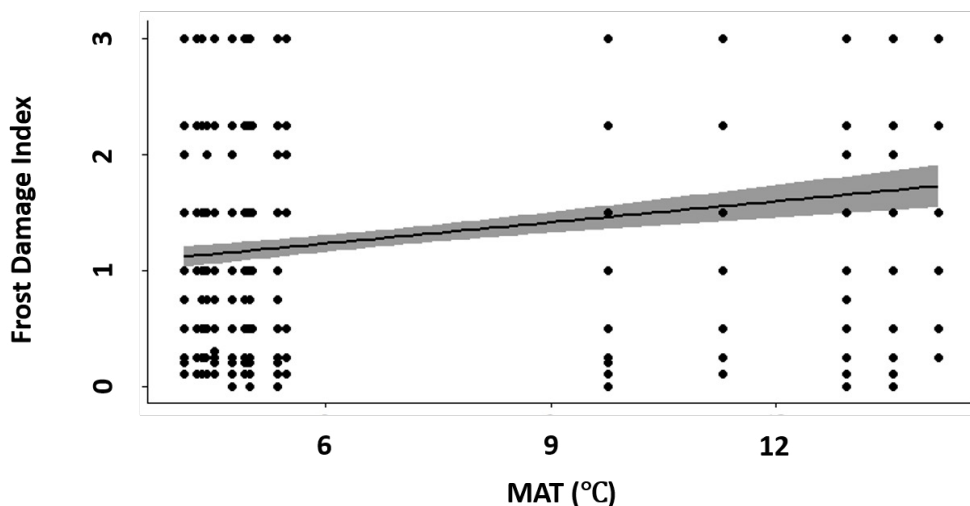


Figure 4.—Positive correlation observed for linear regression of *Q. rubra* frost damage with respect to seed source mean annual temperature (MAT) at the Ford common garden. β_0 , β_1 , and R^2 values are 0.87 FD, 0.06 FD/°C, and 0.044, respectively.

Seed Source Mean Annual Temperature had a Significant Effect and a Positive Correlation on *Quercus rubra* Seedling Frost Damage

Linear regression analysis found seed source MAT has a significant effect on the degree of frost damage experienced by *Q. rubra* seedlings (Table 2). The boxplot analysis of these data shows the wide distribution of the frost damage index within and between each *Q. rubra* population (Fig. 3). Our regression analysis helps explain the differences between the provenances, revealing a significant, positive correlation between the degree of frost damage sustained and the seed source MAT of the *Q. rubra* seedlings (Fig. 4). A low R^2 value was found for this regression analysis (Fig. 4), demonstrating that seed source MAT explains a small amount of the variability for the frost damage index.

DISCUSSION AND CONCLUSIONS

In our initial hypothesis, we stated that the response of the *Q. rubra* population to environmental and site conditions would be dependent on the provenance seed source climate variables. This hypothesis is based on the principal that ecological selective pressures influence a population's genetic structure within a species (Lowe 2017). Results from a previous study conducted by Etterson et al. (2020) support our initial hypothesis. Their provenance study, which investigated the performance of Minnesotan *Q. rubra* populations using a common garden located in the northern edge of the species' range, found that the southern populations showed greater survival and growth when compared to their northern counterparts (Etterson et al. 2020).

Our ANCOVA analysis of *Q. rubra* seed source MAT and aboveground biomass index revealed findings similar to Etterson et al. (2020) and supported our initial hypothesis. At both common garden sites, during both the 2019 and 2020 growing seasons, we found that *Q. rubra* estimated aboveground biomass (reported by the BI values) increased with the increasing seed source MAT (Fig. 2). We found that populations collected from the southern regions of the *Q. rubra* range, the provenances with warmer seed source MAT, such as populations 18, 21, 27, 28, and 29, had on average greater biomass (Figs. 1, 2 and Table 1). This demonstrates that in the absence of late spring or early fall frosts, we observe faster growth of *Q. rubra* from southern provenances grown in northern latitudes.

During the 2020 growing season, our linear regression analysis of seed source MAT and biomass found a four times steeper slope at the Ford common garden site (Fig. 2B). When comparing the data distribution between the populations, we found that the biomass averages for a population are greatest at the Ford common garden site in 2020 (Fig. 1B), a result similar to what has been reported by Etterson et al. (2020).

Assisted migration is a forest management tool for adapting an existing population to future climate change conditions by the intentional introduction of foreign seed stocks (Minteer and Collins 2010, Pedlar et al. 2012). Often, this form of assisted migration involves the movement of southern provenances into the northern range or leading edge of the current species range. This is intended to add to an existing provenances climate change resilience. However, movement of population genotypes that are not matched with the growing patterns of an established population could increase the existing populations risk for frost damage (Aitken and Hannerz 2001). Thus, forestry assisted migration needs to strike a balance between maximizing a population's growth under climate change and limiting injury caused by late spring or early fall frosts (Schreiber 2013). From our initial hypothesis, we would predict that *Q. rubra* populations with greater seed source MAT would experience a greater degree of frost damage. Our regression analysis of the 2021 frost damage revealed that the degree of damage sustained is positively correlated to a populations seed source MAT (Fig. 4). The populations 6, 21, and 29 had the highest frost damage index (Fig. 2, Table 1). The degree of frost damage sustained by populations 21 and 29 is supportive of our initial hypothesis, since these populations were collected from our southern-most sites and had the highest seed source MATs. A higher frost damage index was observed for population 6, an interesting result compared to other populations within the same provenance (Nara Nature Park trail, Houghton, MI: populations 5, 6, 7, 8 and 9). Although this population had a similar mean frost damage index to populations 21 and 29, the lower quartile of population 6 shows is considerably lower than these southern populations (Fig. 3).

With regards to frost damage and assisted migration, studies of growth optimization versus survival optimization have already been investigated for some tree species. Schreiber et al. (2013) found that the northward migration of trembling aspen (*Populus tremuloides*) only slightly delayed growth for southern provenances. Their study concluded that assisted migration of southern trembling aspen provenances to the northern latitudes had either positive or neutral effects on a population growth and survival. Their results highlight a need for future experiments investigate if frost damage has a greater effect on *Q. rubra* provenance growth and survival.

The data we present here complements studies such as Kriebel et al. (1976), Etterson et al. (2020), and Leites et al. (2019) and helps to understand the physiological and growth responses of oak provenances in common garden experiments. Results such as these are necessary to make informed decisions on forestry assisted migration, which may soon be the norm to save populations or entire species from anthropogenic-caused extinction.

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The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

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Conference Presentations Published in *Forest Ecology and Management*

The following articles were published in *Forest Ecology and Management*, Virtual Special Issue: Bridging Science and Management for the Future of Northern Hardwood Forest Ecosystems – select papers from the Northern Hardwood Conference 2021.

- Kern, C.C.; Dickinson, Y.L. 2022. **Introduction to special issue “Bridging science and management for the future of northern hardwood forest ecosystems”**. *Forest Ecology and Management*. 505: 119880. <https://doi.org/10.1016/j.foreco.2021.119880>.
- Rogers, N.S.; D’Amato, A.W.; Kern, C.C.; Bédard, S. 2022. **Northern hardwood silviculture at a crossroads: sustaining a valuable resource under future change**. *Forest Ecology and Management*. 512: 120139. <https://doi.org/10.1016/j.foreco.2022.120139>.
- Draper, M.C.; Kern, C.C.; Froese, R.E. 2021. **Growth, yield, and financial return through six decades of various management approaches in a second-growth northern hardwood forest**. *Forest Ecology and Management*. 499: 119633. <https://doi.org/10.1016/j.foreco.2021.119633>.
- Foppert, J.D. 2022. **Worse off on purpose: an economic analysis of deliberate forest degradation**. *Forest Ecology and Management*. 504: 119771. <https://doi.org/10.1016/j.foreco.2021.119771>.
- VanderMolen, M.S.; Knapp, S.P.; Webster, C.R.; Kern, C.C.; Dickinson, Y.L. 2021. **Spatial patterning of regeneration failure in experimental canopy gaps 15–24 years post-harvest**. *Forest Ecology and Management*. 499: 119577. <https://doi.org/10.1016/j.foreco.2021.119577>.
- Willis, J.L.; Walters, M.B.; Farinosi, E.J. 2021. **Can coppicing planted saplings improve the growing position of mid-tolerant northern hardwood tree species in harvest gaps?** *Forest Ecology and Management*. 483: 118893. <https://doi.org/10.1016/j.foreco.2020.118893>.
- Curtis, P.; Sullivan, K.; Smallidge, P.; Hurst, J. 2021. **AVID: A rapid method for assessing deer browsing of hardwood regeneration**. *Forest Ecology and Management*. 497: 119534. <https://doi.org/10.1016/j.foreco.2021.119534>.
- Smallidge, P.J.; Chedzoy, B.; Curtis, P.; Sims, K. 2021. **Evaluating the construction and effectiveness of slash walls at the perimeter of regeneration harvests to exclude deer**. *Forest Ecology and Management*. 497: 119529. <https://doi.org/10.1016/j.foreco.2021.119529>.
- The following article was presented at NHC 2021 but published after the special issue.**
- Bédard, S.; Raymond, P.; DeBlois, J. 2022. **Northern hardwood regeneration dynamics 10 years after irregular shelterwood and mechanical control of understory American beech**. *Forest Ecology and Management*. 511: 120142. <https://doi.org/10.1016/j.foreco.2022.120142>.

Conference Presentations, Posters, and Virtual Tours

TUESDAY June 15, 2021

Daily Schedule (all times in CST)

Note: Posters and virtual tours available all day on event portal

TIME		Maple E-Room	Basswood E-Room	Birch E-Room
Keynote Presentations	8:00 AM	Welcome & Technology Intro Christel Kern, Greg Edge Heather Berklund - Wisconsin State Forester	(none)	(none)
	8:15 AM	Regional views of the northern hardwood forest resource and its research-management history Christel Kern, Anthony D'Amato, Steve Bédard, Nicole Rogers	(none)	(none)
	9:00 AM	Menominee Tribal Enterprises "The Forest Keepers": The Menominee forest-based sustainable development tradition Adrian "Dusty" Miller, Anthony Waupochick	(none)	(none)
9:35 AM		Break, 15 minutes	Break, 15 minutes	Break, 15 minutes
Keynote Presentations	9:50 AM	The northern hardwood resource: A market perspective William Luppold, Matthew Bumgardner	(none)	(none)
	10:25 AM	Science-management collaboration is no longer an option: It's essential Susan Stout, Andrea Hille, Barbara McGuinness, Alejandro Rojo de Sedas	(none)	(none)
11:00 AM		Lunch, 1 hour	Lunch, 1 hour	Lunch, 1 hour
12:00 PM		Comparison of structural and compositional attributes of northern hardwood forests in Michigan and Minnesota, United States Marcella Windmuller-Campione	Using irregular systems to optimize value growth in southern Ontario maple forests Peter Williams	Factors influencing economic maturity for hard maple Michael Demchik, Niles Timilsina, Joel Kaminski
12:20 PM		Emergent properties of deadwood in canopy openings: a response of the wood-inhabiting fungal community to manipulation of forest structure Lili Perreault, Jodi A Forrester, David J Mladenoff	Climate change vulnerability assessment at Apostle Islands National Lakeshore Peggy Burkman	Testing value development and future stand conditions using the individual-tree selection method in WI forests Forrest Gibeault
12:40 PM		A marked reduction in the growth rate of sugar maple following the accumulation of climatic stress events in southern Quebec, Canada Guillaume Moreau, Alexis Achim, David Pothier	Timeless and thoroughly modern: Maple syrup production in the 21st century Mark Isselhardt	At which diameter does sugar maple reach financial maturity at the northern edge of its range? François Guillemette, Filip Havreljuk
1:00 PM		Choice of silvicultural system influences internal wood characteristics of sugar maple Yvette L. Dickinson, Christel C. Kern, Robert J. Ross, Xiping Wang	Sustainable tapping guidelines for modern maple sap collection practices Abby K. van den Berg, Timothy D. Perkins, Mark L. Isselhardt	Good silviculture will increase productivity and value over time: A 72-year history in a northern hardwood forest Kevin Evans
1:20 PM		Break, 15 minutes	Break, 15 minutes	Break, 15 minutes
1:35 PM		Group Presentation (1:35 to 2:35 PM) Lessons from the land: A new approach to use site-level information to guide climate adaptation Stephen Handler, Ashlee Lehner, Matt Huseby, Harvey Tjader, Brad Hutnik, John Kotar, Maria Janowiak	Group Presentation (1:35 to 2:35 PM) Modern maple sugaring and northern hardwoods management Group Presentation: Mark Isselhardt, Abby van den Berg	Group Presentation (1:35 to 2:35 PM) Hardwood markets in 2020 and beyond Group Presentation: Brian Brashaw, Judd Johnson, Troy Brown, Robert Ross
2:35 PM		Conference Round Table (part 1 of 2)	(none)	(none)
3:05 PM		End Conference Day	End Conference Day	End Conference Day

WEDNESDAY June 16, 2021

Daily Schedule (all times in CST)

Note: Posters and virtual tours available all day on event portal

TIME	Maple E-Room	Basswood E-Room	Birch E-Room
8:00 AM	Group Presentation (8:00 to 9:40 AM) NH-SEED: A holistic experiment to revisit classical and test novel silvicultural systems in a changing world C.R. Webster, Y. Dickinson, T. Bal, C. Bartlick, K. Brzeski, R.E. Froese, B. Gusick, A. Helman, S. Hupperts, M.C. Kelly, J.M. Schmierer, K. Schnieder, and J.D. Wolfe	Group Presentation (8:00 to 9:40 AM) Alternative silvicultural systems, tree regeneration success and deer use in northern hardwood forests Mike Walters, Gary Roloff, Jason Hartman, Catherine Henry, Evan Farinosi, Melissa Starking	Can coppicing plant saplings improve the growing position of mid-tolerant northern hardwood tree species in harvest gaps? John L. Willis, Michael B. Walters, Evan J. Farinosi
8:20 AM	1. Introducing the Northern Hardwood Silviculture Experiment to Enhance Diversity (NHSEED) // Dickinson, Bal, Bartlick, Brzeski, Froese, Gusick, Hupperts, Kelly, Schmierer, Schnieder, Webster, and Wolfe	1. Rationale and design of alternative silvicultural systems experiment in Michigan's northern hardwood forests // Roloff and Walters	Considerations for creating canopy gaps in northern hardwood forests Dustin Bronson, Christel Kern, Amanda McGraw, Teresa Pearson, Laura Reuling
8:40 AM	2. Initial regeneration and understory plant community responses to the NHSEED treatments // Bartlick, Dickinson, Hupperts, Froese, and Webster	2. Pre-harvest stand regeneration composition and associated driving factors // Henry	Tree Regeneration response and spatial patterning of midtolerant saplings in variable-sized group selection harvest gaps in northern Wisconsin, USA David K Schnake, Jodi A Forrester, Andrew J. Sanchez-Meador, David J Mladenoff, Craig Lorimer
9:00 AM	3. Assessing soil compaction following a winter harvest of northern hardwoods // Kelly	3. Early vegetation and browse responses to harvest treatments // Farinosi	Long-Term evolution of composition and structure after repeated group selection over eight decades Nicole Rogers, Anthony D'Amato, William Leak
9:20 AM	4. Demographic response of small mammals to experimental silviculture treatments // Wolfe, Gusick and Brzeski	4. Pre-harvest and post-harvest deer-use following alternative silviculture // Starking	Opening-creation alone may do little to increase diversity in contemporary northern hardwoods: Results from two long-term group-selection experiments Samuel Knapp, Christopher Webster, Christel Kern, Matt Vander Molen
9:40 AM	5. Novel application of iDNA tool for measuring small mammal community biodiversity via silphid beetles // Bal, Schnieder and Brzeski	5. Roundtable Q and A: From project planning to results implementation, research-management partnerships are critically important // Hartman, Walters, Roloff, Farinosi, Henry, Starking	
9:40 AM	6. Northern hardwood silviculture: Preferences among family forest owners in the western Upper Peninsula of Michigan // Kelly and Helman		
9:40 AM	Break, 15 minutes	Break, 15 minutes	Break, 15 minutes
9:55 AM	Beech bark disease tolerance: An emerging concept in American beech management Laura Kenefic, David Houston, William Livingston, Stacy McNulty, Bethany Muñoz Delgado, Lauren Keefe	Genetic considerations for assisted migration efforts in northern hardwood trees Carolyn Pike	AVID: A rapid method for assessing deer browsing of hardwood regeneration Paul D. Curtis, Peter J. Smallidge, Kristi L. Sullivan
10:15 AM	Regeneration development 10 years after partial cutting and mechanical control of beech in northern hardwood stands Steve Bedard, Patricia Raymond, Josianne DeBlois	Quantifying drought adaptation in red oak species: Linking physiology to gene expression James Rauschendorfer, Victoria Peck, Stephanie Frantti, Carsten Kuellheim	Deer browse of hardwood regeneration controlled by slash walls Peter J. Smallidge, Brett J. Chedzoy, Paul D. Curtis
10:35 AM	Interfering Forest Vegetation Management decision matrix Brett Chedzoy, Peter Smallidge	Assisted migration use in a browsed landscape: Can we predict susceptibility to herbivores? Emilie Champagne, Alejandro A. Royo, Jean-Pierre P. Tremblay, Patricia Raymond	Increasing awareness and integration of exotic earthworm impacts into forest management decisions Tara L. Bal, Julie Grinstead, Yvette L. Dickinson, Andrew J. Storer
10:55 AM	Lunch, 1 hour	Lunch, 1 hour	Lunch, 1 hour
12:00 PM	Nonparametric individual-tree growth models for the Northern Forest Neal F. Maker, John D. Foppert	Northern hardwoods through the eyes of practitioners: A review of case studies on the Great Pennsylvania sedge treatments using herbicide Lakes Silviculture Library and various application methods Eli Sagor, Marcella Windmuller-Campione, Matt Schultz, Tom Piikkila, Jerome Wotachek	
12:20 PM	Group Presentation (12:20 to 1:20 PM) Lessons learned from climate adaptation projects in northern hardwood forests Maria Janowiak, Stephen Handler, Matt Dallman, Peter Clark, Jessica Wikle	From soup to nuts: A single-tree selection harvest from conception to completion Bradley M. Hutnik	Manage for quality hardwoods and multiple age classes through release of crop trees and allowing for regeneration of red oak and paper birch through variable density thinning Tom Parkin
12:40 PM	1. Adaptation in action: Managing northern hardwoods with climate change in mind // Janowiak & Handler	Building on the stand adaptive capacity for the design of adaptation silviculture treatments: Example of application in the SylvAdapt multi-stress experiment Frédéric Doyon, Philippe Nolet, Audrey Maheu, Ana Rita de Sousa e Silva, Isabelle Aubin	Comparing fall vs. winter shelterwood harvests Dennis J. Thompson
1:00 PM	2. Leveraging Work from On-the-Ground to General Practice: Lessons Learned from Caroline Lake // Dallman		
	3. Structural and compositional outcomes across a gradient of forest adaptation treatments in northern hardwoods // Wikle		
	4. Adaptive Silviculture for Climate Change: examining strategies for adapting northern forests to global change // Clark	The effects of various treatments on tree species regeneration: Comparison of multiple mid-term experiments Philippe Nolet, Sylvain Delagrangue, Steve Bédard, Simon Bilodeau-Gauthier, Donald Blouin, Gilles Joannis	Five-year growth response of a 41-year-old yellow birch stand to commercial thinning Alexandre Morin-Bernard, François Guillemette, Steve Bédard
1:20 PM	Break, 15 minutes	Break, 15 minutes	Break, 15 minutes
1:35 PM	Conference Round Table (part 2 of 2)	(none)	(none)
2:05 PM	End Conference Day	End Conference Day	End Conference Day

Hosting Policy for the Biennial Northern Hardwood Conference (NHC), version 1

NHC2021 Biennial Meeting Development Committee^{1*}

BACKGROUND

The northern hardwood type occupies millions of acres of forest land in the eastern United States and Canada, representing one of the most economically important and ecologically diverse forests in eastern North America. Northern hardwood silviculture is diverse and complex and has been the focus of extensive research for over 80 years. Today, managers continue to seek innovative sustainable management solutions to address the expanding challenges facing this forest type, including serious threats such as invasive species, inadequate tree regeneration and shifts in composition, herbivory, climate change, nitrogen deposition, and forest fragmentation. A large-scale conference to discuss and summarize the current science and management of northern hardwood forests has not been held since the 1980s. Over 2018–2021, a diverse group of research and management professionals developed a repeating conference concept to learn, share, and discuss cutting-edge science and innovative management practices to sustain healthy and productive northern hardwood forests now and into the future.

VISION

The Northern Hardwood Conference will be...

- An engaging and reoccurring biennial event where participants learn, share, and discuss ideas to sustain forest uses and values now and into the future.
- An event with an applied management and silviculture emphasis.
- An inclusive, welcoming event to all interested in the current and future status of northern hardwood forests.
- A go-to event where cutting-edge science and innovative management practices/uses are exchanged.
- A responsive event that highlights urgent needs in northern hardwood forest ecology and management.

GOALS

The Northern Hardwood Conferences will...

- Foster relationships among research/academia/management/industry/conservation sectors
- Present science syntheses and latest findings
- Showcase conventional and alternative management practices
- Keep abreast on trends, issues, and opportunities in the products industry
- Identify knowledge gaps and future research needs

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*Version 1 was drafted and approved by the NHC 2021 Biennial Meeting Development Committee, which consisted of members from the Lake States (Christel Kern, Greg Edge, Mike Walters, Chris Webster), Northeast (Tony D'Amato, Laura Kenefic, Peter Smallidge, Kevin Evans), and southeastern Canada (Gaetan Pelletier, Steve Bedard, Frederik Doyon, Alexis Achim, Trevor Jones).

MISSION

- Host geographically rotating, biennial Northern Hardwood Conferences to facilitate knowledge exchange and showcase applications and uses of northern hardwoods first-hand by various organizations and regions.

HOSTING POLICY

To maintain the vision, goals, and mission of the Northern Hardwood Conference (NHC), a hosting policy was created by the Biennial Meeting Development Committee in 2020-21. The policy will aid host organizations to plan and interested organizations decide if hosting is a possibility. The hosting policy will also aid in selection of location if multiple locations are put forth for the same conference year.

Hosting Principles

These fundamental principles will serve as guides for identifying and determining the conference location and host organization for NHC:

1. Since the primary function of NHC is to serve the full range of the northern hardwood forest type, the conference location will rotate biennially between Canada, Lake States, and northeastern United States to allow for full participation and reduced travel for each region to participate in-person every few years. The rotation pattern among the three regions can vary over time to meet the other hosting principles, but, on average, will rotate equally among regions to “cross-pollinate” knowledge and practice.
2. The hosting organization(s) will:
 - Have one or more people dedicated to being conference chair during the 2+ years of conference planning.
 - Have potential resources to initiate planning (e.g., staffing, sponsorship, synergy, ...).
 - Will plan conference logistics, either through the host organization or other conference planning service (note: efficiencies may be gained by using the same firm as the previous host).
 - Disseminate evaluation surveys to participants and share results with the next conference’s host.
 - Archive and document the information exchanged at meetings through proceedings, journal special issues, and other formats (host decides on best format(s)).
 - Target registration to less or equal to \$350 USD/\$465 CAD by leveraging expenses (e.g., facility fees) with sponsorships (and other grants, in-kind, etc.) to reduce costs to participants.
 - Maintaining a mixed format of 2 meeting days and 1 field day - mixed format is essential but the length and order may be influenced by the experiences at previous conferences and by host.
 - Aim for hybrid in-person and virtual options to encourage as much participation as possible across the northern hardwood range.
 - Give funds remaining after conference expenses are paid (if available) to the next conference host to be used as student travel scholarships.
 - Share planning documentation and lessons learned with the next conference host.

- Announce the next host, year, and location on the current conference website and at the meeting.
3. Because the NHC is focused on exchanging knowledge and showcasing practice, the hosting location will aim for an in-person conference with these criteria.
 - The conference facility
 - can hold ~300 people.
 - has floor layout for concurrent sessions, posters, exhibitors, and other meeting formats as needed.
 - is convenient to amenities, such as lodging, food service, and airport.
 - The nearby airport is mid-sized or larger in terms of number of airlines and flight options.
 - The field sites are <2 hours from conference facility for tours. (Optional pre- and post-conference tours/training can be arranged by host for sites further away.)
 - Selected dates should avoid overlapping with other major conferences that are of interest for the NH forest science and management community
 4. Virtual options are encouraged to increase participation for those with travel restrictions.
 5. The hosting policy should be reviewed and updated after each conference. The reviewers should include representatives from each region. Decisions should be made by majority rules and, as needed, by informed leader(s) (i.e. conference chair(s)).

Hosting Schedule

Based on the above principles, NHC conferences are scheduled for the following locations and hosted by the following organizations:

Year	Country	Province/State	City	Organization(s)
2021	USA	WI	Green Bay/Virtual	USDA FS NRS & WI DNR
2023	Canada	NB	Fredericton	NHRI & UNB
2025				
2027				

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