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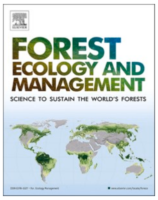

Review

Northern hardwood silviculture at a crossroads: Sustaining a valuable resource under future change

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ABSTRACT

Northern hardwoods are an economically, ecologically, and culturally important forest type spanning the upper latitudes of the United States and the lower latitudes of Canada. The prevalence and value of these forests have driven silviculture research for over a century. During this time, silvicultural approaches have varied widely, searching for scenarios to meet traditional commodity-based and diversifying ecological forestry objectives. To better understand this forest type and the spectrum of appropriate silvicultural options, we analyzed regional inventory data from the United States and Canada and synthesized decades of scientific studies. Calculated overstory tree (stems $\geq$ 12.5 cm diameter at breast height) metrics show common structural conditions across mature northern hardwood forests and dominance of sugar maple (*Acer saccharum*). However, density and composition metrics for established reproduction (saplings 2.5 to 12 cm dbh) emphasize challenges for establishing and maintaining economically and ecologically valued trees species broadly and regionally. Our work underscores the variation in northern hardwoods within and across its distribution, driven by characteristics like disturbance regimes, land use history, and ownership patterns. We conclude maintaining this important forest type amid climate uncertainty and associated effects, like proliferation of exotic insects and diseases, requires recalibration of historically applied silvicultural systems and application of emerging tools.

1. Introduction

The northern hardwoods are a wide-ranging forest type, covering approximately 20 million hectares across the northern United States and southern Canada (Leak et al., 1987; Rowe, 1972). Broadly, the northern hardwood forest (NHF) is defined by dominance of three temperate, deciduous species, sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), and American beech (*Fagus grandifolia*) (Eyre, 1980; Halliday, 1937). Compositional variability within this larger forest classification, however, is well documented (Beaudoin et al., 2017). Abundance of other species within the beech-birch-maple forest, as the NHF is also known (Gawler and Cutko, 2018), is driven by regional and site-level factors including land-use history (Foster, 1992; Orwig and Abrams, 1994; Schulte et al., 2007), species silvics (Burns and Honkala, 1990; Tubbs et al., 1983), wildlife dynamics (Horsley and Marquis, 1983; Sage et al., 2003), disturbance regimes (Lorimer and White, 2003), and local site attributes (Barnes et al., 1982; Leak, 1978; Nichols, 1935).

The NHF provides a spectrum of ecological, social, and economic benefits, although specifics vary by region, species abundance, or structure. Broadly the NHF plays a critical role in forest nitrogen and carbon cycles, provides vital habitat for mammal (Jensen et al., 2012), birds (Doyon et al., 2005), and amphibians (Hocking et al., 2013), as well as enhanced water quality (Kellison and Young, 1997; Zipper et al., 2011). Colorful fall foliage draws in tourists each year, contributing to local economies, as do specialty products like maple syrup and chaga (*Inontus obliquus*) (Brydon-Williams et al., 2021; Matthews and Iverson, 2017). The NHF is used for traditional forest products, including timber and pulpwood. In the context of global climate change, the NHF is important for carbon storage (Ford and Keeton, 2017) and area of exploration for carbon markets (Russell-Roy et al., 2014).

Silviculture, the art and science of managing forests for diverse, human defined goals, is an essential tool for maintaining the NHF and the wide array of products and associated values. Decades of research

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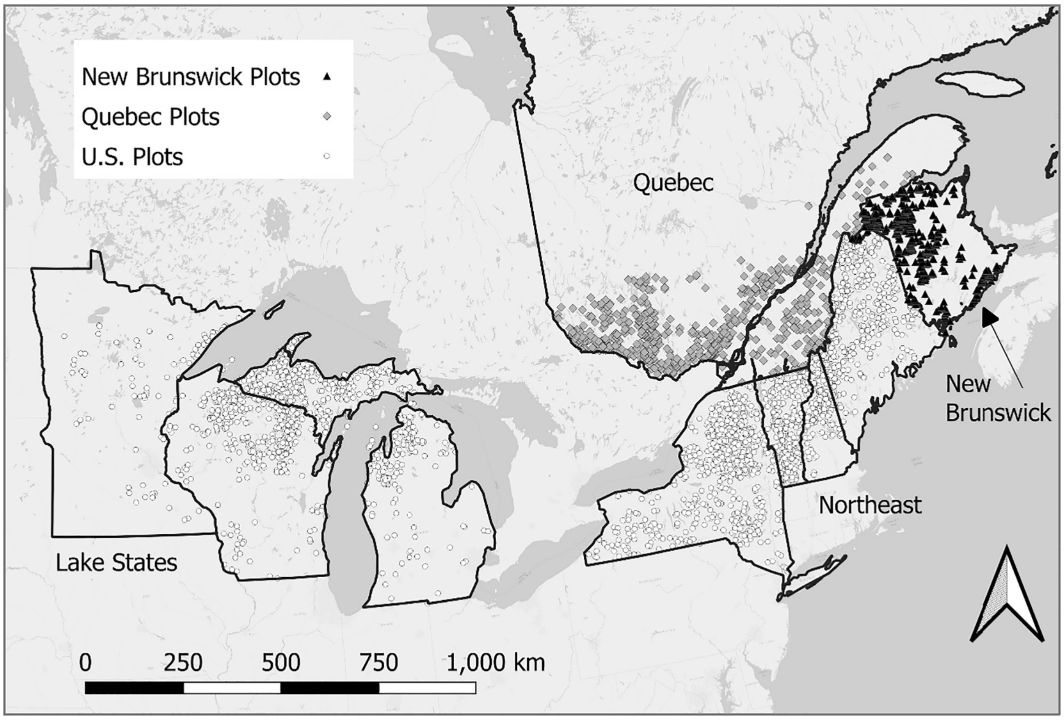

Fig. 1. Location of regions within the larger northern hardwood forest (NHF) and locations of forest inventory plots used in the Present-Day NHF analysis described below.

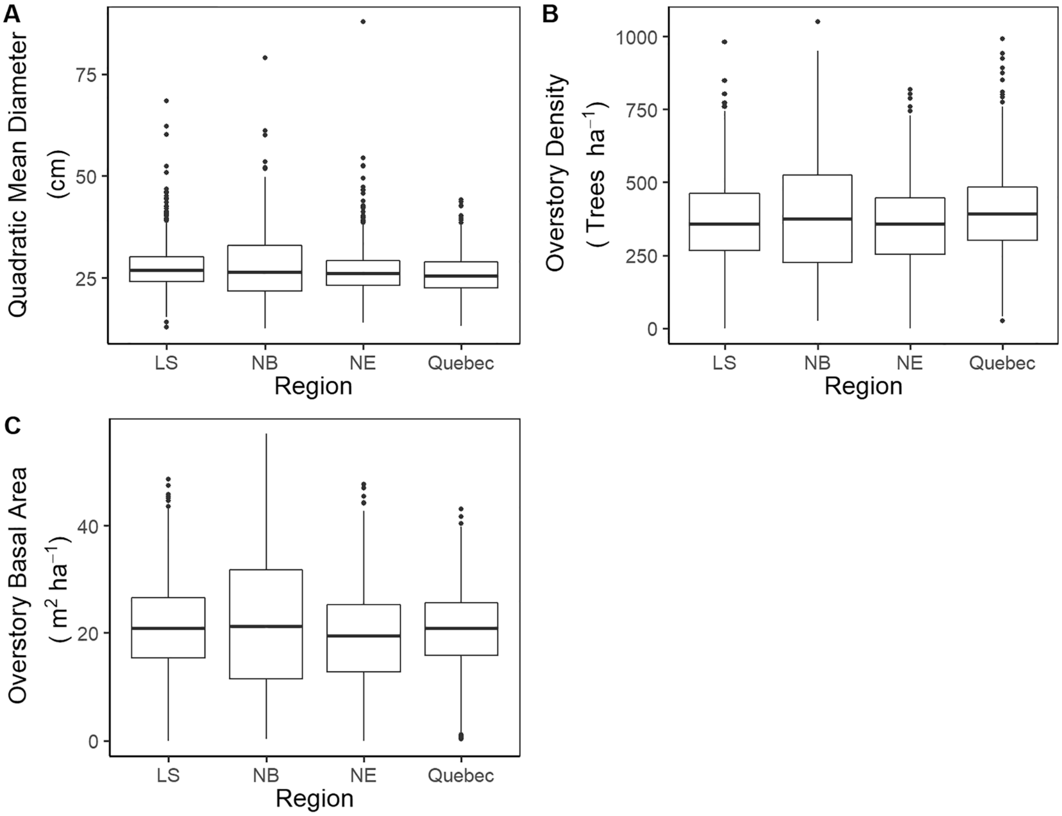

Fig. 2. Boxplots of average overstory tree (≥12.5 cm dbh) attributes by region A: quadratic mean diameter (cm), B: overstory density (trees per hectare), C: overstory basal area (m^2 per hectare). LS = Lake States United Stations, NB = New Brunswick Canada, NE = Northeast United States, and Quebec = Quebec Canada.

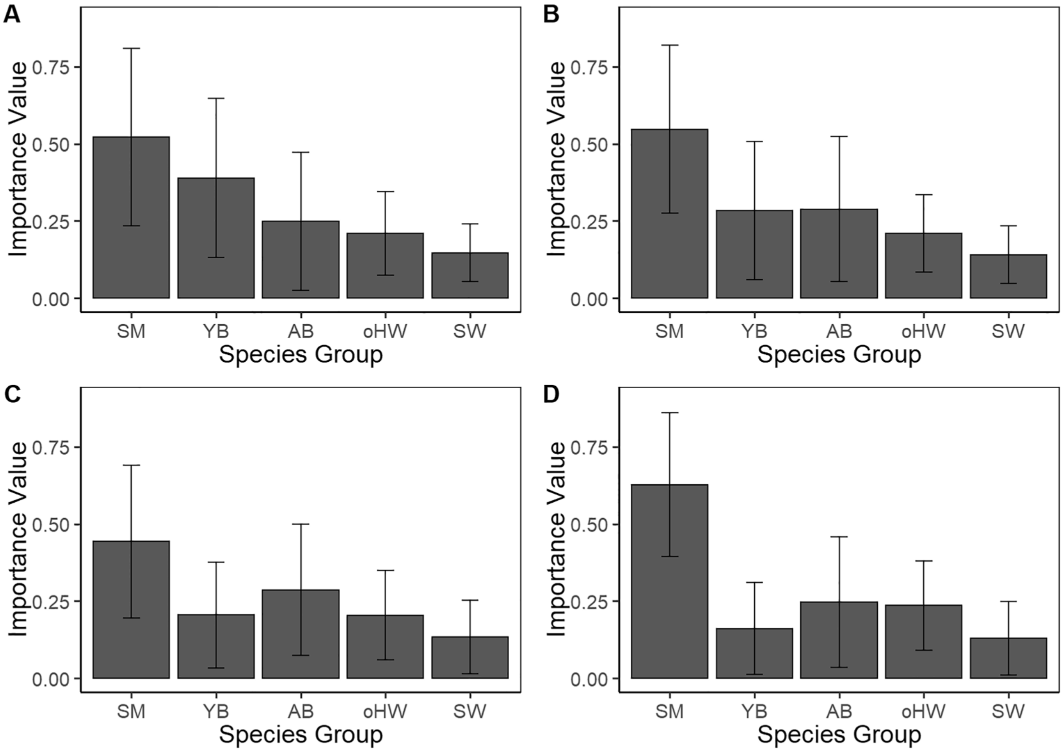

Fig. 3. Species dominance for overstory trees (≥12.5 cm dbh) by region. Dominance is measured by mean species importance; error bars represent standard deviation. A: New Brunswick, B: Quebec, C. Northeast United States, D. Lake States United States. AB = American beech, SM = sugar maple, YB = yellow birch, oHW = other hardwood species, SW = softwood species. For the mathematical calculation of species importance values see Appendix 1.

have explored how silvicultural systems shift species abundance and structure, generate sustained wood supplies, preserve forest health, and address regeneration challenges. However, the NHF continues to develop with changing forest ownership patterns (Butler et al., 2016; Sass et al., 2020) and transforming environmental conditions (Halofsky et al., 2018), warranting a detailed look at silvicultural tools for maintaining this important forest type. In this review, we define the NHF, broadly and regionally, consider how current species abundance and structural conditions reflect underlying site characteristics, disturbances, and present and past ownership patterns. We also examine the history of silviculture in the NHF and the management options in the face of novel and evolving challenges.

2. Northern hardwood regions

The northern hardwoods are a temperate forest type, occurring in humid and cool locations with average annual precipitation between 80 and 130 cm and range in elevation from 150 to 460 m (Seymour, 1994; Stearns, 1997). Warmer summers are balanced by winters cold enough to maintain a continuous snowpack. Proximity to large bodies of water, including the Great Lakes, the Atlantic Ocean and the St. Lawrence River, moderate temperatures and increase precipitation locally (Stearns, 1997).

2.1. Regional definitions

Across the range of the NHF are distinct regions, defined by unique abiotic and biotic conditions. For this work, we have designated four regions using geopolitical boundaries: the Lake States of the United States (Minnesota, Wisconsin, and Michigan), the Northeast United States (New York, Vermont, New Hampshire, and Maine), and the Canadian province of Quebec and the Canadian province of New Brunswick (Fig. 1). We acknowledge the NHF occurs in states or provinces adjacent to those listed but confined our geographic focus to complete geopolitical units. For example, the NHF is a component of forests in Pennsylvania, but acreage is limited relative to New York, approximately 1 million vs. 5.6 million hectares respectively (Albright, 2018, 2017). For each region, we consider site characteristics, disturbance regimes/agents, and ownership patterns/land-use history. Although there are additional characteristics specific to each region, we believe these three are essential for understanding inherent species abundance and structure, and appropriate silvicultural options. Beyond the regions we have defined, extensions of the NHF occur in the central and southern portion of the United States, known as Appalachia and the transition to mixedwood forests (80%-20% softwood and hardwood mixtures) in the eastern US and Canada. However, we have excluded these forests from our review as they contain southern hardwood or northern conifer species, respectively, beyond this work.

2.2. Present-day northern hardwood forest

Before considering the attributes of each region mentioned above, we evaluated the structure and species abundance of the current NHF using available forest inventory data (https://fia.fs.fed.us, https://www2.snb.ca/content/gnb/en/departments/erd.html, https://mffp.gouv.qc.ca/; see Appendix 1 for methods). Trends are clear across the broader NHF and by region in the overstory (trees ≥ 12.5 cm dbh) and established reproduction layers (saplings 2.5 to 12 cm dbh). Calculated overstory structural attributes (quadratic mean diameter [QMD, cm] and density [trees per hectare and m^2 per hectare of basal area]), are similar among the defined regions, based on overlapping box-and-whisker plots and comparable median values (Fig. 2). Median values of QMD, approximately 10 cm (Fig. 2A), basal area, approximately 20 m^2 ha^{-1} (Fig. 2B), and density, approximately 375 trees ha^{-1} (Fig. 2C), were not visibly different by region. However, New Brunswick has a broader range of structural conditions relative to other regions (Fig. 2). Compositionally, the overstory of the NHF is dominated by sugar maple, evidenced by the high species importance values (IV, %)

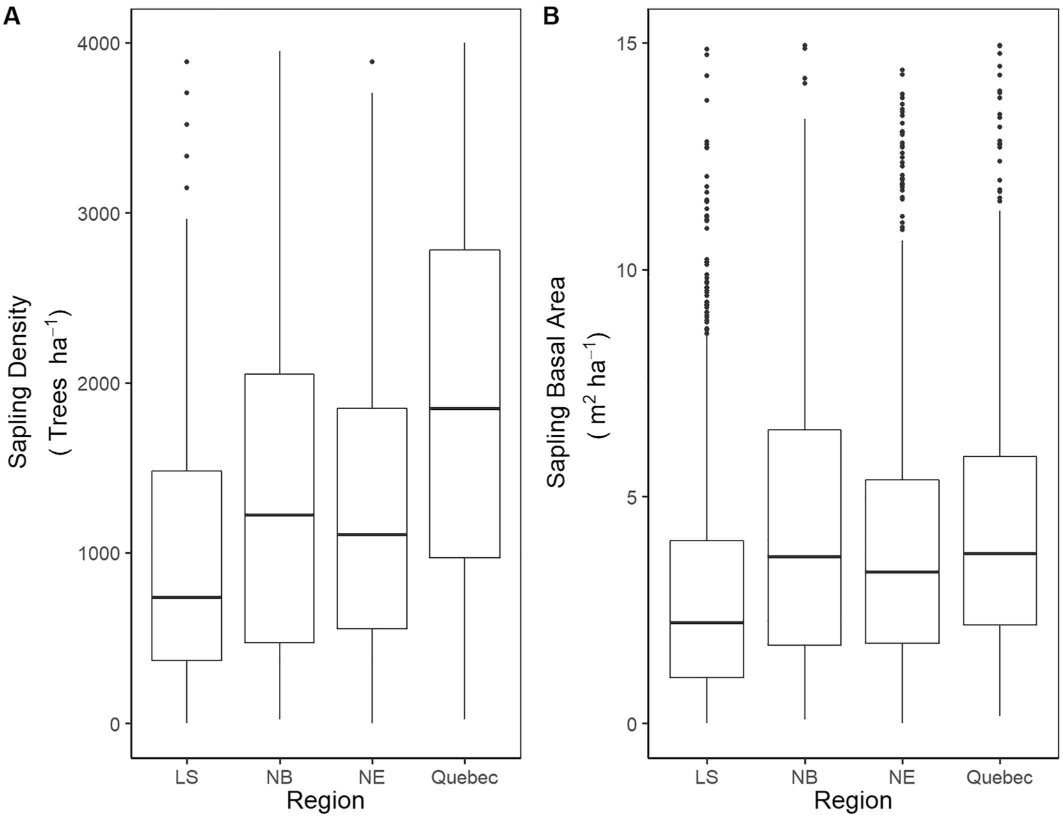

Fig. 4. Boxplots of established reproduction (saplings 2.5 to 12.4 cm dbh) structural metrics by region: A. density (trees per hectare) and B. basal area (m^2 per hectare). LS = Lake States United Stations, NB = New Brunswick Canada, NE = Northeast United States, and Quebec = Quebec Canada.

compared to other species (Fig. 3). Though, dominance of sugar maple compared to other species varies by region. Importance of the other two defining northern hardwood species, yellow birch, and American beech, varies as well by region (Fig. 3). Considering established reproduction (saplings 2.5 to 12 cm dbh) at the same locations, regional trends emerge. Although abundant, the distributions of sapling density (m^2 per hectare of basal area and trees per hectare) are wide (Fig. 4). In eastern regions, median densities exceeded 1000 stems per hectare and 4 m^{2}ha^{-1} of basal area (Fig. 4). Median densities were lowest in the Lake States (Fig. 4A). Sugar maple is the dominant regenerating tree species in the Lake States, but not in other regions where American beech was more abundant based on species importance values (Fig. 5). Yellow birch had the lowest importance value of all regenerating tree species assessed across each region. Each region also had a substantial component of softwood established reproduction (Fig. 5). Median values of sapling density (trees per hectare) meet or surpass regional regeneration guidelines for the NHF (Leak et al., 1987; Marquis, 1975; Tubbs, 1977), but species abundance results emphasize the challenge of regenerating more economically valued species i.e. sugar maple and yellow birch, relative to American beech. This challenge is highlighted in the compositional disconnect between the overstory and established reproduction in stands across the NHF (Fig. 3 and Fig. 5). In the following sections, we consider the role of site characteristics, disturbance regimes/agents, and forest ownership/land-use history in creating these current conditions regionally and broadly in the NHF.

2.3. Site quality & species abundance

Site quality across the NHF is variable but tied closely to soil characteristics and landscape features. Soils in the NHF are classified as podzols (Lull, 1968; Robitaille and Saucier, 1998; Seymour, 1994) developing after the retreat of the last glaciers approximately 10,000 years ago (Stearns, 1997). The glaciated landscape fluctuates from poorly drained depressions to well-drained topographic features (Stearns, 1997). Divergence in soil characteristics regionally and from stand-to-stand impact species abundance and growth potential. The calcareous parent material in the Lake States generates more productive soils than in eastern regions of the NHF (Schaetzl et al., 2012). Granitic parent material in the east creates rockier, less fertile soils, although bands of calcareous bedrock exist in portions of New York, Vermont, Northern Maine, southwestern Quebec, and eastern New Brunswick (Fahmy et al., 2010; Lull, 1968; Stearns, 1997). Changes in soil quality, specifically nutrient availability, is closely tied to species abundance in the NHF (Johnson et al., 1987; Schmoldt et al., 1985). Sugar maple, a preferred species for its high economic and social value, increases in abundance on enriched sites with well drained soils (Lindsey et al., 1965; Nyland, 1999). However, the high nutrient requirements for sugar maple often limit the occurrence of pure stands without direct management intervention (Godman et al., 1990). In our overstory and established reproduction analysis, elevated importance of sugar maple in the Lake States (Fig. 2, Fig. 4) likely reflect the higher site quality of the region (Godman et al., 1990) combined with management that favors more shade tolerant species (Crow et al., 2002; Neuendorff et al., 2007) (See Section 3). Prevalence of American beech in eastern regions (Fig. 2, Fig. 4) reflects the underlying range of the species, which stretches from eastern Wisconsin, across southeastern Canada, and the eastern United States (Stephanson and Coe, 2017). The current range of American beech is seemingly controlled by environmental conditions (Woods and Davis, 1989). Within this context, the abundance of American beech in eastern regions likely reflects lower site quality too, which makes site demanding species, like sugar maple, less competitive (Tubbs and Houston, 1990; Ullah and Moore, 2009). The history of beech bark disease (BBD), which triggers root suckering (see Section 2.3), in the eastern regions is also suspected to influence prevalence of American beech.

Assessing and understanding site quality is a fundamental

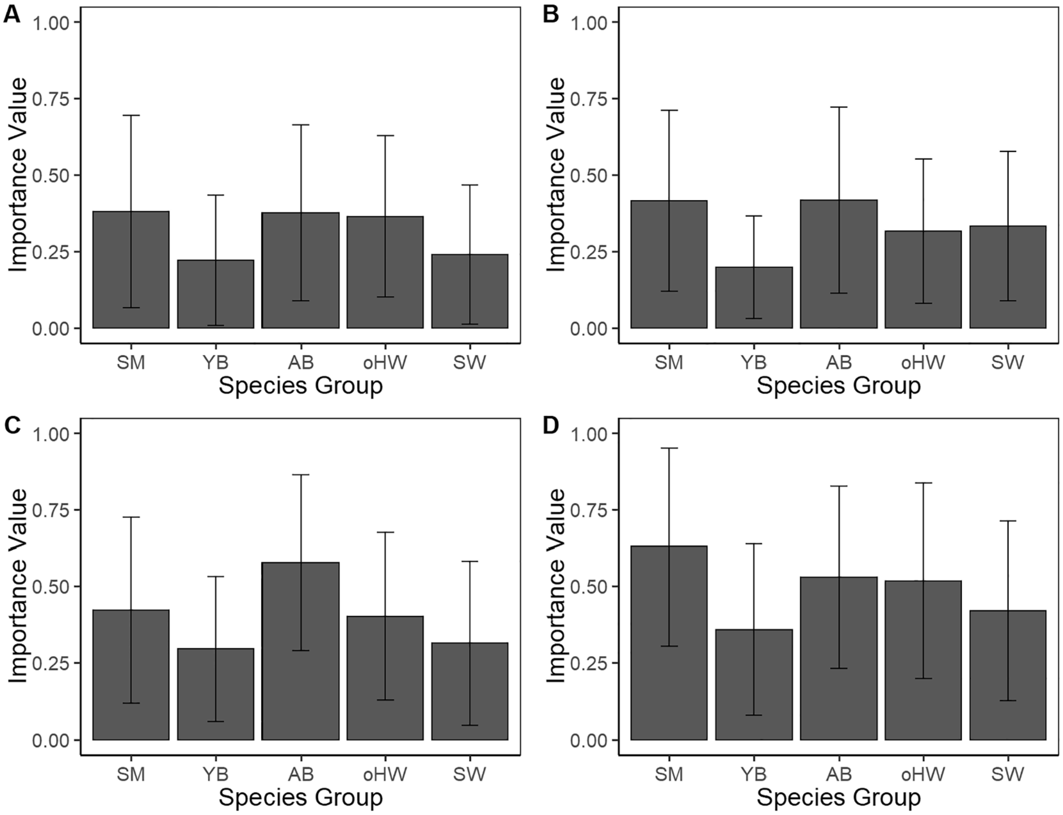

Fig. 5. Species dominance for established reproduction (saplings 2.5 to 12.4 cm dbh) by region. Dominance is measured by mean species importance; error bars represent standard deviation. A: New Brunswick, B: Quebec, C. Northeast United States, D. Lake States United States. AB = American beech, SM = sugar maple, YB = yellow birch, oHW = other hardwood species, SW = softwood species. For the mathematical calculation of species importance values see Appendix 1.

underpinning of silviculture (Ashton and Kelty, 2018; Smith et al., 1997). Site quality, specifically soil fertility and drainage, are recognized as key controls on the species establishment and stand-level productivity in the NHF (Henry et al., 2021; Post, 1962). Further, silvicultural systems, when linked with site characteristic, in addition to other important attributes, are more likely to achieve species compositional goals (Willis et al., 2016). For example, in the eastern United States, sites on washed glacial till managed with group selection retained yellow and paper birch (*Betula papyrifera*) even with a component of American beech, while sugar maple was best maintained with single-tree selection, but only on enriched sites (Leak, 1980). Careful consideration of the site has been an integral part of selecting appropriate silvicultural systems within the NHF for nearly half a century (Baker, 1934; Leak, 1978; Marquis, 1975).

2.4. Disturbance regimes and disturbance agents

We propose three primary disturbance factors related to the results from our overstory and established reproduction analysis: disturbance regime, ungulate browsing, and beech bark disease. Similar to site quality and associated characteristics, natural disturbance regimes and disturbance agents influence the structural and compositional dynamics of the NHF (Bormann and Likens, 1979; Oliver, 1981). Commonly, natural disturbance events in the NHF are defined by size, severity, and frequency (Lorimer and White, 2003). For example, disturbances may be classified as local, low-intensity and frequent to regional, severe, and infrequent (Lorimer and White, 2003) although disturbances beyond this gradient are also important for successional and developmental dynamics (Franklin et al., 2002; Frelich and Lorimer, 1991). Small-scale disturbances, occurring every 50–200 years, establish canopy gaps in the forest between 4 and 1,135 m^2 in size (Seymour et al., 2002). These small openings favor growth of shade tolerant species like sugar maple, American beech, and eastern hemlock (*Tsuga canadensis*), a common associate in the NHF (Canham, 2010). Sugar maple and beech are highly shade tolerant, persisting under low light conditions for decades. Larger stand replacing events occur every 800 to 9,000 years, disrupting 1 to > 80,000 ha (Seymour et al., 2002). The scale and frequency of *meso*-scale disturbances are intermediate relative to small and large-scale events, playing an equally important role in development of these forests (Jenkins, 1995; Wood et al., 2009). In the NHF, a spectrum of disturbance types occur across the scale of disturbance size, intensity, and frequency (Lorimer and White, 2003). For example, ice storms are associated with small-scale, insect outbreaks or drought with *meso*-scale, and fire with stand-replacing events (Brewer and Merritt, 1978; Krasny and Digregorio, 2001; Pederson et al., 2014; Rustad and Campbell, 2012). Wind disturbances, while often a small-scale, can also be a *meso*-scale, or even stand-replacing (Bormann and Likens, 1979; Rentch et al., 2010).

Increased canopy openings are important for establishing shade intolerant and mid-tolerant species such as yellow birch, paper birch, and white ash (*Fraxinus americana*) (Archambault et al., 1998; Godman et al., 1990; Tubbs, 1977). The low importance of yellow birch in the sapling size classes (Fig. 5) could signal greater prevalence of small-scale disturbances, both naturally occurring and human induced (management), across the NHF (Godman and Krefting, 1960; Leak, 1980), as well as differences in litter quality (Hupperts et al., 2020). The structural similarities in the overstory between regions (Fig. 2, Fig. 4) are likely explained by overarching disturbance regimes and similar management histories (Brown et al., 2018).

In addition to the broader disturbance regimes associated with the NHF, distinct disturbance agents are important to regional dynamics. Browse by white-tailed deer (*Odocoileus virginianus*) is one such example. Although influence of heavy deer browsing can be negative and long-lasting across the NHF (Boucher et al., 2004; Nuttle et al., 2013;

Table 1
Plot count by dataset used to analyze the current northern hardwood resource.

Dataset	# of Plots
United States	4042
New Brunswick	434
Quebec	1046

Tanentzap et al., 2011), the impact of over-browsing is especially clear in the Lake States where deer populations can exceed 17 per km^2 (Walters et al., 2016). Significant changes in forest composition, overall abundance of reproduction, and increased susceptibility to invasive species have been observed in forests with deer densities above 4–6 per km^2 (Alverson et al., 1988; Horsley et al., 2003; Walters et al., 2016). Many studies show the importance of controlling deer populations to ensure forest regeneration, but management can be difficult (Miller and Graefe, 2001; Royo and Stout, 2017; Witmer and DeCalesta, 1991). Local deer populations vary with winter severity, hunting policies, and ranges of matriarchal groups (Nesslage et al., 2001; Sage et al., 2003). Further, deer management is a topic of interest to a wide range of stakeholders whose objectives do not always align (Woolf and Roseberry, 1998). We suspect lower sapling densities observed in the Lake States compared to other regions of the NHF are partially because of this browse phenomena (Fig. 2, Fig. 4). In the eastern regions, where BBD triggers prolific root sucking in smaller size classes (see below), competitive interactions between American beech and more economically desired species (sugar maple and yellow birch) are further exacerbated by heavy browse pressure as American beech is less palatable to deer (Tierson et al., 1966). The combined dynamics of BBD and browse presumably affected the elevated abundance of established American beech reproduction (Fig. 5).

Beech bark disease first arrived in the eastern United States and Canada at the turn of the last century, permanently altering the NHF (Houston, 1975; Shigo, 1972). Today, the BBD complex (scale insect *Cryptocococcus fagisuga* and fungus *Nectria coccinea* var. *faginata*) is widespread, although the impact of the disease is not consistent from region to region. In the Lakes States as well as northern portions of Quebec, BBD is a more recent arrival, creating different American beech dynamics relative to locations where the disease has been active for nearly a century, including the northeastern U.S. (McCullough and Wieferich, 2015). Three stages of BBD are recognized: the advancing front, killing front, and aftermath zone (Houston, 1994). The advancing front represents the earliest stages of the disease complex with the scale insect visible on infected trees, but with limited presence of the fungus. The killing front is associated with widespread mortality of American beech, particularly on large diameter trees, whereas the aftermath zone is defined by mortality of most large-diameter American beech, some remaining resistant trees, and numerous small, root-origin sprouts (Houston, 1994; Twery and Patterson, 1983). Much of northeastern North America is in the aftermath zone, while central and far northern locations are in the advancing front (Giencke et al., 2014). The shade tolerant nature of American beech and the ability to prolifically sucker following harvest or injury complicates management of hardwood forests, especially in systems where sugar maple and yellow birch are preferred (Jones and Raynal, 1988; Tubbs and Houston, 1990). The high importance of American beech in the established reproduction size classes, particularly in the eastern United States and southeastern Canada, is attributed to the long history of BBD in those regions (Fig. 3, Fig. 5).

In addition to BBD, the spruce budworm (*Choristoneura fumiferana*) is another disturbance agent that has shaped the structure and composition of eastern NHFs, particularly in Quebec and New Brunswick. Outbreaks of spruce budworm, a native insect, and subsequent mortality of softwoods, namely balsam fir (*Abies balsamea*), shifted composition of mixed conifer-hardwood forests (mixedwoods) to more hardwood dominance (Danneyrolles et al., 2016; Dupuis et al., 2020). Compositional relics from previous disturbances likely contribute to the disconnect between current overstory and established reproduction species abundance (Fig. 3, Fig. 5).

Beyond the disturbance agents we have identified, numerous others exist, regionally and broadly. We acknowledge these disturbances have impacted the current structure and species abundance of the NHF. However, we have focused on the disturbance agents above as we see clear connections between them and the results from our overstory and established reproduction analysis.

2.5. *Forest ownership and land-use history*

Like site characteristics and disturbance agents, the influences of present and past ownership types, patterns, and objectives are seen throughout the current NHF. In the United States, forests are largely privately owned and within that classification, predominantly family owned (Sass et al., 2020). Property size within the private, family-owned classification ranges from 0.4 to 3.6 ha (Butler et al., 2021). However, ownership patterns for remaining forestland differ between the Lake States and Northeast. In the Lake States, the dominant land ownership group, family ownership, is followed by federally- and state-owned forests, while, in the Northeast, private corporations follow family ownership (Sass et al., 2020). Small, private individual and families often see timber extraction as a secondary goal (Leak et al., 2014; Rickenbach and Kittredge, 2009). Rather, these small landowners manage their woodlands for wildlife habitat and aesthetics (Kelty et al., 2003). For larger private landowners, including real estate investment trusts (REITs) or timber management organizations (TIMOs), the management emphasis is on traditional forest products and return for investors (Mendell, 2016). Across Canadian forestland, public ownership is most prevalent, although ownership patterns differ between Quebec and New Brunswick too. Ninety percent of Quebec's forests are Crown land, while 50% of New Brunswick is Crown land (The State of Canada's Forests Annual Report, 2019). The additional forestland land in New Brunswick is divided among private ownership and industrial free holdings, 29 and 18% respectively. The high percentage of public ownership in Canada can cause unique management opportunities and challenges. Integration of societal expectations in natural resources management can be found across many forest ownership (Moffat et al., 2016). However, balancing the social license to practice forestry with the legal license is especially true in Canada where forest managers are stewards of a publicly owned resource (Beckley, 1998; Chambers and Beckley, 2003). An example of public input changing forestry practices in Canada is the banning of chemical herbicide on Crown lands in Quebec (Thiffault and Roy, 2011). In other regions of the NHF chemical herbicide is still used as a tool for controlling competing vegetation, namely American beech (Kochenderfer et al., 2004; Nyland et al., 2006).

Present day ownerships are part of a long history of management in the NHF, beginning with Indigenous Peoples. Early use of forest resources varied by region and forest type, but documentation of periodic burning, manipulation of wildlife, and harvesting for traditional and non-traditional forest products exists (Bromley, 1935; Emery, 2002; Patterson and Sassaman, 1988). In southern New England for example hardwood species such as oak (*Quercus* sp.) and American chestnut (*Castanea dentata*) were favored after fires, often set for agriculture purposes, (Abrams, 2000; Orwig and Abrams, 1994) while sugar maple, yellow birch, and American beech were relegated to smaller areas because of their low fire tolerance (Fuller et al., 1998). Canadian forests saw similar manipulation of fire regimes by First Nations people, although documentation is limited (Dupuis et al., 2020). The northern hardwoods have further been influenced by detrimental government policies during the 1800 s and 1900 s that limited land ownership by Indigenous Peoples. An exception to these policies is the Menominee tribe of Wisconsin (Mausel et al., 2017; Trosper, 2007). The Menominee have practiced sustainable forest management through thoughtful removal of mature trees and tending to the residual forest stand for over 150 years (Kern et al., 2017; Pecore, 1992). Today, their forestland offers a sharp contrast to other forests across the Lake States with histories of more degrading forest practices (Sands and Abrams, 2011).

The arrival of European settlers to North America in the early 1600 s triggered wide-spread land clearing, for construction and agriculture, shifting the age and species abundance dynamics of the NHF (Cogbill et al., 2002; Hermy and Verheyen, 2007). Heavy partial harvesting of red spruce (*Picea rubens.*), balsam fir, and eastern white pine (*Pinus strobus*) across temperate forests in the late 19th and early 20th century, moving composition from mixedwoods to more hardwood dominance (Bryant, 1917; Dupuis et al., 2011; Linn, 1918; Pinto et al., 2008; Westveld, 1949). In pure hardwood stands, high quality sawlogs were selectively removed, leaving unmerchantable trees of poor quality and vigor (Blum and Filip, 1963; Hall et al., 2002). Structure of the NHF changed again in the 1980 s and 1990 s with increased demand for hardwood pulp favoring removal of smaller stems (Luppold and Sendak, 2004). Today, these land use changes have resulted in large areas of even-aged northern hardwoods in regions recovering from agricultural abandonment (eastern regions) and clearcutting (Lake States) of the past centuries and irregular, often poor stand conditions in other regions where exploitative partial cuts prevailed (Kenefic and Nyland, 2006). Forest conditions created by past ownership and historical objectives, presumably create the compositional disconnect between overstory and established reproduction highlighted in our present-day analysis of NHF conditions (Fig. 3 and Fig. 5).

3. Silviculture history in the northern hardwood forest

Silvicultural systems for the NHF have long been governed by compositional and structural goals (Eyre and Neetzel, 1937; Jensen, 1943; Leak et al., 1969). However, effective management also incorporates the underlying attributes driving the current forest condition. Early research explored management systems for sustained yield of timber; a common guiding paradigm for research in many forest types in the early 20th century (Seymour, 2004; Stout et al., 2006). Foundational studies assessed harvest intensities of different silvicultural systems and subsequent effects on forest composition and structure (Eyre and Zillgitt, 1953; Gilbert and Jensen, 1958). These early works established silvicultural recommendations that continue to be used in the NHF and inspired silvicultural guides for other reaches of the northern hardwood range (Arbogast Jr, 1953; Leak et al., 1987; Majcen et al., 1984; Pond et al., 2014). Successive research has investigated species response to habitat (Barnes et al., 1982; Carmean, 1999), interference of competing vegetation with tree regeneration (Nyland et al., 2001; Willis et al., 2015), and how to emulate natural disturbances (Coates and Burton, 1997; Franklin et al., 2007; Hanson and Lorimer, 2007) in an effort to generate consistent outcomes and effective silvicultural systems. But forest conditions continue to advance as do management objectives (Butler and Leatherberry, 2004). This advancement includes management for global climate change (Bolton and D'Amato, 2011; Parker et al., 2000; Webster et al., 2018), improved emulation of underlying ecological principles (D'Amato and Palik, 2021; Kern et al., 2019) and broader ecosystem services in general (O'Hara, 2016). Given the increasingly complex nature of northern hardwood forests and the evolving challenges to management, silvicultural responses require careful evaluation of all available options.

Throughout the history of northern hardwood silviculture, use of and preference for different systems has oscillated between extremes (O'Hara, 2002; Smith, 1972). Unfortunately, such oscillation may leave valuable tools and management strategies out of consideration (Kern et al., 2014; Pond et al., 2014). In the context of the NHF, numerous studies have shown successful development of these forests with a wide range of silvicultural systems (Burns, 1983) and conversely, inconsistent results when the same method is applied across different conditions or locations (Bédard and Majcen, 2003; Neuendorff et al., 2007). As such, preference for silvicultural systems fluctuates between extremes of even and uneven-age approaches over time (Smith, 1972).

3.1. Even-age systems

Even-age forests do occur in the NHF after natural, stand-replacing disturbances. However, this age structure is more frequently the product of historical, intensive land-use or more recent harvesting history. Clearcutting and uniform shelterwood systems have been applied in the region since the early period of formalized forest management to create even-age conditions (Leffelman and Hawley, 1925); however, these approaches have not experienced the wide-spread popularity of uneven-age silvicultural systems such as group and single-tree selection. In part, the limited application of even-age silviculture at a broad scale is due to historical and ongoing public reaction to these silvicultural systems relative to other, less intensive approaches (Hannah, 1988; Kelty et al., 2003). This is especially true of clearcutting. Public opposition to clearcutting is widespread with many associating the practice with environmental decline and detrimental management (Bliss, 2000). In some instances, public responses to clearcutting have initiated policy debates and reform in an effort to regulate use on federal (Fairfax and Achterman, 1977; Spurr, 1981) and private lands (Steelman and Ascher, 1997). Yet, despite constraints to these approaches, clearcutting has been demonstrated as an economical and efficient method for managing northern hardwoods, favoring more shade intolerant species (Hornbeck et al., 1986). In central New York, clearcutting increased species diversity in the newly developing cohort and resulted in stands with high stocking of commercially valuable species including sugar maple and yellow birch (Wang and Nyland, 1993). In New Brunswick, clearcutting promoted new germinates relative to advance reproduction, mostly yellow birch and pin cherry (*Prunus pensylvanica*) (Roberts et al., 1980). In the Lake States, 5-acre clearcuts successfully regenerated economically desired species in old-growth NHF, but not in second-growth, due to advance reproduction on site and diverse seed sources in the former and not the latter (Metzger and Schultz, 1984). Complete removal of the overstory in clearcuts also creates needed habitat for early successional bird species (Costello et al., 2000; Yamasaki et al., 2014) as well as mammals, reptiles, and amphibians that rely on young forest conditions (DeGraaf and Yamasaki, 2003; Moorman et al., 2011). Although benefits of clearcutting are clear for some conditions, ecological concerns exist as well, especially reduction in biodiversity of non-tree species and loss of mature forest legacies critical to sustaining certain species and processes in regenerating forests (Rudolphi et al., 2014). Increasing mature tree retention, specifically large biological legacies, is an increasingly common strategy to address these concerns (Gustafsson et al., 2010)

Shelterwood systems are another even-age method where public opinion or policy guidelines make widespread implementation difficult (Hannah, 1988). Outcomes vary by the number of entries, time of harvesting, and density of the overwood, but when these attributes are appropriately matched to stand conditions and objectives, shelterwood cutting is an effective method for regenerating northern hardwood forests in all NHF regions (Godman and Tubbs, 1973; Hannah, 1988). Research from the Adirondack region of New York showed ample regeneration of yellow birch, sugar maple, and white ash in deer exclosures following a two-stage shelterwood, outside exclosures regeneration was dominated by American beech and hobblebush (*Viburnum lantanoides*) (Curtis and Rushmore, 1958). Kelty and Nyland (1981) saw similarly abundant reproduction of desirable species using a two-stage shelterwood in combination with hunting to reduce populations of white-tailed deer and pretreatment mist blowing of herbicides to remove competing vegetation. In the Allegheny region of the United States, shelterwood cutting successfully regenerated commercial valuable northern hardwood species in combination with herbicide site preparation (Ristau et al., 2011). A crucial component of shelterwood systems is layout of the final harvest to remove the overwood. Jacobs (1974) observed 35% of established reproduction was damaged during the removal cut in a northern hardwood stand, but overall reproduction was successful due to a major regeneration event following the initial cut. Yet, economic, and operational difficulties in removing the overwood (Leak et al., 2014) and landowner preference for less visible disturbance (Kelty et al., 2003) remain reasons uniform shelterwood systems have not been more widely adopted in northern hardwood forests of the northeast U.S. However, spatial, and temporal variations of the shelterwood system, including integration of reserve trees or more complex distribution of the overwood can be used to meet broader ecological goals (Ashton and Kelty, 2018; Palik et al., 2020).

3.2. *Uneven-age systems*

Preliminary guidelines were developed for single-tree selection based on theoretical balanced stand conditions aimed at sustaining a regular supply of timber over time and improving growth of the residual stand (Eyre and Zillgitt, 1953). Long-term research across the range of northern hardwoods has demonstrated successful regeneration and increased stand quality with careful application of single-tree selection, especially with efforts for American beech control and deer browse impacts (Jones et al., 1989). The implementation of single-tree selection has been most appropriate on sites where an increased abundance of tolerant species that yield high value products are desired results (Keyser and Loftis, 2013). Efforts to regenerate and maintain mid-tolerant species after repeated applications of single-tree selection have not been as successful (Johnson, 1984; Webster et al., 2018). The inherent favoring of large, shade tolerant trees have spurred extensions of traditional single-tree selection systems to generate late successional forest habitat (Keeton, 2006). Yet, for larger scale applications, single-tree selection requires a high skill level for marking implementation (Brockway et al., 2015). Further, the challenges of creating and maintaining a truly balanced stand structure, as well as questions about the popriateness, have increased the interest in alternative options for northern hardwood management (Hicks, 1998; Janowiak et al., 2008).

Group and patch selection are additional strategies for northern hardwood management, noted for maintaining uneven-age structure while recruiting mid-tolerant and tolerant species (Poznanovic et al., 2013). Long-term data from New England demonstrated that increased light in group selection relative to single-tree selection increased the component of desirable species, namely yellow birch and sugar maple, by providing a competitive advantage over beech (Leak and Filip, 1977). Early results in Ontario found similar compositional trends after group selection harvesting (Falk et al., 2010). This approach may also offer productivity benefits, as a study of northern hardwoods in Wisconsin showed increased growth in small group openings relative to single-tree selection openings with productivity reaching an asymptote as gaps size increased above 100 m^2 (Webster and Lorimer, 2005). While still considering structure of the stand, group selection offers increased flexibility in target diameter distributions where marking is driven by presence of advance reproduction or pockets of economically mature trees (Leak and Gottsacker, 1985). Patch selection, also a method of uneven-aged management, is similar to group selection but creates larger canopy openings, between 0.1 and 0.8 ha in size or greater than two tree lengths (Ashton and Kelty, 2018; Leak et al., 2014). Openings are created using stand area regulation, while removing single trees throughout the surrounding matrix (Leak et al., 2014; Nyland, 2005). Uneven-aged management with emphasis on greater canopy disturbance is important for regenerating and retaining more mid and intolerant hardwood species (D'Amato et al., 2015; Yamasaki et al., 2014) Additional and essential benefits of selection silviculture with larger openings include control of American beech and increased habitat for wildlife, specifically songbirds. In NHFs where a persistent understory of American beech exists, the larger canopy openings, relative to single-tree selection, remove beech advance reproduction and create an early competitive advantage for more commercially desirable species (Leak, 2005). Larger openings in group and patch selection create early seral habitat too, especially in the first years following harvest (DeGraaf and Yamasaki, 2003). These stages of forest succession and development provide important structural and composition conditions for breeding songbirds (Costello et al., 2000). Generating this habitat with existing silvicultural options is particularly important as songbird populations decline (Bonnot et al., 2018).

Group and patch selection have become increasingly popular methods for managing northern hardwood forests, but as seen in other common silviculture systems, are not without their challenges. Balancing ecological benefits with operational efficiency is one such challenge, particularly when considering the layout of openings. Establishing groups or patches is a tool for increasing structural diversity in more homogenous stands (D'Amato and Palik, 2021), but arbitrary location of openings disregards the benefits of these treatments for accommodating spatial variability i.e. simultaneous removal of economically mature overstory trees and release of well stocked advance reproduction (Minckler, 1972; Murphy et al., 1993). Considering appropriate orientation and shape of openings is also necessary to ensure consistent results for goals of sustained timber supply and predictable species composition (Marquis, 1965). Over time, group and patch selection can increase the complexity of the forest by diversifying age structures and species abundance, which has strong ecological benefits (Hanson et al., 2012). However, successfully managing forests with group selection, like many silvicultural tools, requires careful consideration of multiple factors beyond opening size alone, including microsites, local disturbance regimes, and competing vegetation (Kern et al., 2017).

3.3. *Hybrid systems*

An alternative approach to more rigid even and uneven-aged systems is the irregular shelterwood system. Primarily in eastern Canada, but also in New England (Peterson and Maguire, 2004) and to some degree the Lake States (Helman et al., 2021), irregular shelterwoods have been proposed as a hybrid of traditional even and uneven-aged management for mixedwood and hardwood forests (Raymond et al., 2009). Irregular shelterwood systems are an approach to capture the ecological complexity, particularly species abundance and structure, of forests following mesoscale disturbances (Raymond and Bédard, 2017). The continuous cover and expanding gap versions of this system have increased spatial and temporal flexibility relative to traditional shelterwood, single-tree, and group selection methods to meet these objectives (Raymond et al., 2009). In Quebec, Canada continuous cover and extended irregular shelterwood systems have been employed to rehabilitate impoverished northern hardwood stands following repeated selective cutting (Bédard et al., 2014). For stands with a low percentage of acceptable growing stock and high component of American beech, Bédard et al. (2014)found irregular shelterwood systems may be more appropriate than single-tree selection if desired species are those that could be regenerated in groups; however, cutting cycle lengths would need to be greater than those used in single-tree selection given heavier volume removals at each entry. Initial results for irregular shelterwood studies are promising in terms of increasing species and structural diversity, metrics of increasing importance when assessing forests for changing climate and market conditions (Christel C Kern et al., 2017).

4. Northern hardwood silviculture, climate change, and options for the future

As we consider the prospects of the NHF, our look forward must be framed in the context of global climate change and the ambiguity of future forest conditions. Presently, forests store approximately 45% of terrestrial carbon, and have been highlighted as a critical component of climate change mitigation strategies (Bonan, 2008). These mitigation strategies include silvicultural recommendations for carbon storage and sequestration as well as new carbon markets and emphasis on longerlived forest products (Ameray et al., 2021; Landry et al., 2021; Winans et al., 2016). However, there remains uncertainty about the frequency of future forest disturbances, shifts in resource availability, and ultimately, movement of species ranges (Dale et al., 2001; Iverson et al., 2001; Sykes et al., 1996). It is this uncertainty, that requires careful consideration as we evaluate silvicultural options moving forward.

Field observations and model scenarios offer some insight as we contemplate the vulnerability of species or forest communities to changing environmental conditions (Iverson et al., 2008; Nagel et al., 2017). For sugar maple and yellow birch, two defining species of the NHF, abundance across their ranges is expected to decrease (Peters et al., 2020). This decrease is anticipated to be most severe for sugar maple where largest populations could be limited to zones of climate refugia (Oswald et al., 2018). Occurrence of American beech, conversely is increasing throughout portions of its range (Bose et al., 2017). Shifts in historical species composition is further exacerbated by alterations in natural disturbance regimes and invasive diseases and insects (Lovett et al., 2016). For example, non-native and invasive earthworms have no historical context in the NHF but are triggering declines in forest health through depletion of leaf litter and soil nutrients important for regenerating key species, like sugar maple (Burtelow et al., 1998; Callaham et al., 2006). Prevalence of ash species (*Fraxinus* spp.) in the NHF is also on the decline following fatal infestations of the invasive emerald ash borer (*Agrilus planipennis*) (DeSantis et al., 2013). As temperatures warm, the invasion range of the emerald ash borer is predicted to increase, directly threatening the ecological and cultural values associated with ash forests (Iverson et al., 2016; Looney et al., 2017). Beech bark disease and forest tent caterpillar (*Malacosoma disstria*), a native defoliator, are other important disturbance agents that may benefit from warmer climates, especially during winter months (Dukes et al., 2009). The intensity and frequency of natural disturbances are increasing too, including droughts (Dale et al., 2001), windstorms (Peterson, 2000), and ice storms (Rhoads et al., 2002). The cumulative impact of these changing conditions are large-scale shifts in the structural, compositional, and functional baselines that have long defined the NHF (Churchill et al., 2013). These shifts are not without challenges, but novel circumstances also create unique opportunities to reframe tools and strategies for evolving forests and management objectives.

Managing forests for adaptability and resiliency has been suggested as an approach that may allow forests and forest managers to buffer the uncertainty of future conditions (Millar et al., 2007; Spittlehouse and Stewart, 2003). Analysis of the outcomes of long-term silviculture studies in the Lake States region of the United States found multi-aged approaches, including irregular shelterwoods, may be the most effective at balancing mitigation and adaptation at the stand-level because they capture a wide range of historical disturbances and subsequent forest complexities (D'Amato et al., 2011; Hupperts et al., 2020). Integration of complexity into forest management frameworks can further support ecosystem resilience by retaining diverse species and functional niches, reducing fire, drought, and browse risk, and ultimately, more closely aligning human-managed systems with underlying natural drivers (D'Amato and Palik, 2021; Drever et al., 2006; Kern et al., 2019).

Within the NHF, specific activities such as adaptation planting, could be added to existing or evolving silvicultural systems for further resilience to climate change. Planting species outside their native range, as is the case with assisted migration, can be controversial and requires upfront financial investments (Messier et al., 2019). However, a proactive approach to changing species ranges may limit the mis-alignment between current species distributions and climate conditions (Williams and Dumroese, 2013). Studies within and beyond the NHF found assisted migration efforts, including adaptation plantings, maintained stand-level productivity, conserved endangered species, and increased overall species diversity (Boulanger and Puigdevall, 2020; Dumroese et al., 2015; Duveneck and Scheller, 2015). Clark et al. explored adaptation planting in the northeastern portion of the NHF and their recommendations were cautiously optimistic (2022). Yet, the authors were clear, successful adaptation planting requires consideration of site attributes, like competing vegetation, and preparation for events like elevated summer droughts or unseasonable spring frosts which may be the new climate reality (Clark et al., 2022).

Utilization of slash walls are another example of creative problem solving within the NHF. Although this strategy is relatively novel, early results are promising. Smallidge et al. explored the use of slash walls to mitigate the effects of deer browsing in central New York (2021). Four years after harvesting, seedlings within the slash wall interior had higher height growth than surrounding areas. Additionally, slash wall construction was less expensive than traditional exclosures and provided a use for low-value or non-commercial species (Smallidge et al., 2021). Creating browsing refugia is especially important in the context of climate change, where regenerating preferred species could already be difficult or associated with planting costs (Champagne et al., 2021). The spectrum of changes anticipated for the NHF is wide and the magnitude of impact uncertain but careful modification of existing management strategies and integration of new tools provides a path forward (Keenan, 2015; Price et al., 2001; Spittlehouse and Stewart, 2003).

Flexibility in management is central to development of healthy and well-functioning forest under future uncertainty (Dukes et al., 2009). History in the NHF and other forest types reveals periods of preferences for one extreme of silvicultural options or another (O'Hara, 2002; Smith, 1972) Such actions were restrictive then and would be even more detrimental today. Rather forestry practitioners need to consider all options, including novel tools and modification of existing silvicultural systems, guided by management approaches best suited to their specific objectives and forest conditions (Millar et al., 2007). In the context of changing future conditions, an overriding objective for selection and application of any given approach should be the maintenance of a wide range of structural and functional conditions at the stand and landscape-level as a precautionary strategy for addressing the uncertainties associated with global change impacts (D'Amato et al., 2011; Puettmann, 2011).

5. Conclusions

The northern hardwoods are a geographically broad and highly valued forest type. For decades, silviculture research across the NHF has explored management strategies for balancing a range of objectives, including generating a sustainable yield of timber, restoring ecological diversity, creating wildlife habitat, and maintaining visual aesthetics. In addressing these objectives, silviculture in the NHF has historically fallen into two distinct categories aimed at achieving even-aged or uneven-aged stand structures. Our review of the existing literature, and subsequent analysis of regional inventory data, highlights the value and challenges associated with these silvicultural approaches. Further, our results emphasize structural, compositional, and functional variability of the NHF within and across its range. Silviculture that incorporates this variability is especially important as we look forward to an increasingly uncertain future because of climate change and the proliferation of non-native insects and diseases. Successfully establishing, growing, and maintaining northern hardwoods into the future will require a modification of traditional silvicultural approaches with new and creative tools, such as adaptation planting and irregular systems, to provide the range of options necessary and adapt with emerging management challenges.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Northern hardwood data analysis

Our assessment utilized forest inventory data from the USDA Forest Service Forest Inventory Analysis (FIA) program (https://fia.fs.fed.us), the New Brunswick Department of Natural Resources (https://www2.snb.ca/content/gnb/en/departments/erd.html), the Quebec Ministry of Forests, Wildlife, and Parks (https://mffp.gouv.qc.ca/).

The USDA Forest Service Forest Inventory Analysis program is a national census comprised of a network of permanent sample plots established on a grid system across the United States. The inventory plot is constructed of four, circular 7.2 m radius subplots with nested micro-plots using a radius of 2 m. All trees $\geq$ 12.7 cm dbh are measured on subplots, while saplings (2.5 to 12.4 cm dbh) and seedlings ($<$2.5 cm dbh, height $\geq$ 15.2 cm for softwood species, $\geq$ 30.4 cm for hardwood species) are measured on micro-plots. Field crews re-measure plots on a 5-year cycle with approximately 20% of plots measured each year (Burrill et al., 2018). Data included in this analysis were from the most recent and complete inventory of each state available at the time data acquisition in January 2020. We used the EVALID code 2018 to select all forested plots inventoried in each state between 2012 and 2018. Data were downloaded and extracted using the software R (version 3.6.1 “Action of Toes”, https://www.r-project.org/) and the package rFIA (Stanke et al., 2020).

Forest inventory data for the Canadian province of New Brunswick were obtained from the New Brunswick Department of Natural Resources’ Continuous Landscape Inventory (CLI). Data from the CLI are measured on circular fixed area plots with a nested design. Overstory trees $\geq$ 7.1 cm dbh are measured on 400 m^2 plots and trees $<$ 7.1 cm dbh are measured on 50 m^2 plots. 25% of plots in the CLI network are permanent sample plots (PSPs) measured every five or ten years depending on plot designation. Trees measured on PSPs are tagged and numbered. Remaining CLI inventory data are collected every ten years, trees are not tagged or numbered. Data for this analysis are from the most recent inventory of each plot. Data are stored in excel data files available from the New Brunswick Department of Natural Resources.

The Quebec Ministry of Forests, Wildlife, and Parks created a permanent plot network across the Provence of Quebec beginning in 1970. The network is intended for monitoring of forest dynamics over time and plots are randomly located within strata defined by species subzones. Sampling intensity the northern hardwood subzones is 1 plot per 26 km^2. Overstory trees, saplings, and seedlings are measured with a nested plot design. Trees (9.1 cm to 29 cm) dbh are recorded on a circular 11.3 m radius plots and trees $>$ 29 cm are recorded on a circular 14.1 m plots, saplings, trees 1 to $<$ 9 cm dbh, are recorded on a 3.6 m radius circular plot, and seedlings, stems $>$ 60 cm in height and $\leq$ 1 cm dbh are tallied using two circular 1.13 m plots. Plots are remeasured every approximately every 10 years. For this analysis, we used data from the most recent inventory of each plot. Inventory data were extracted from a Microsoft Access database available through the Quebec Ministry of Forests, Wildlife, and Parks website.

For this analysis, overstory trees are those $>=$12.5 cm dbh. Saplings are classified as trees 2.5 cm to 12.4 cm dbh.

A.1. Study area and plot selection

The study area for this work includes seven U.S. States (Maine, New Hampshire, Vermont, New York, Michigan, Wisconsin, and Minnesota) and two Canadian provinces (New Brunswick and Quebec). To discern regional trends, states were also aggregated into larger ecological blocks. We defined Maine to New York as the northeast region of the U.S., Michigan to Minnesota as the Lake States region. The number of plots per dataset are listed in Table 1.

Across all data sources, we selected a subset of inventory plots classified as northern hardwood based on dominance of three key species, American beech, sugar maple, and yellow birch. We considered a plot to be northern hardwood forest if species abundance by basal area, of each species singly or cumulatively, exceeded 50% for trees $\geq$ 2.5 cm dbh. To prevent selection of mixedwood forests we also limited softwood composition to $<$ 26% by basal area (Vickers et al., 2021). We choose these criteria to capture the broad definition of the northern hardwood forest (Eyre, 1980). Basal area calculations and plot selection were determined using the R statistical package, version 4.0.5 (https://r-project.org). The location of each northern hardwood plot was mapped using QGIS (version 3.12, https://qgis.org/).

A.2. Data analysis

To assess the northern hardwood resource, we evaluated overstory trees and established reproduction for each state/province and region. We contained analysis to attributes we could calculate across all data sources. For overstory trees we considered four attributes, species importance values (IV), quadratic mean diameter (QMD [cm]), density (trees ha^{-1}), and basal area (m^2 ha^{-1}). We determined IV for five species/species groups, American beech, sugar maple, yellow birch, other hardwood, and softwood using the formula $IV = (RDen + RDom)/2$. RDen is relative density and RDom is relative dominance where relative density is defined as the proportion of a given species/species group (tree ha^{-1}) to the total number of species a plot. Relative dominance is the basal area (m^2 ha^{-1}) of a given species/species group compared to total basal area per plot. Relative density was defined as the proportion of a given species (tree ha^{-1}) compared to the total number of species in a cohort. Relative dominance was defined as the basal area (m^2 ha^{-1}) of a given species compared to total basal area in a cohort. Relative density and dominance were expressed as percent of the total. We included QMD as an alternative measure of stage of stand structural development appropriate in forests that may have multiple age classes (Lorimer and Frelich, 1998). Boxplots were generated for each overstory attribute with state/province and region as the independent variable.

Two characteristics were calculated to represent regeneration, density (trees ha^{-1}) and species importance values, as described above. Species specific values were determined for American beech, sugar maple, yellow birch, other hardwood species, and softwood species. All values were calculated for the state/province and region. Analysis for overstory and regeneration data was completed using the R statistical package, version 4.0.5.

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