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THE ROLE OF MANAGED FORESTS IN BIODIVERSITY AND CONSERVATION IN THE ACADIAN FOREST

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EXECUTIVE SUMMARY

J.D. Irving, Limited Woodlands (JDI) has been involved in forest management for over a century in the Acadian forest and maintains a deep commitment to sustainably managed forests and land stewardship. A productive forest ecosystem is one that includes a range of tree, plant and animal species adapted to the local ecosystem and climate. What comprises sustainable forest management has evolved to include a broad range of ecological and societal values, alongside the traditional focus on wood supply.

Adaptive Forest Management allows for evolving knowledge based on sound, fundamental science to be integrated into forestry practice. This report summarizes investments in science and conservation over several decades and describes how JDI has adapted its forest management accordingly. Research helps the company maintain a healthy forest products industry while being better informed stewards of the forests the organization manages. We highlight nine broad research areas that JDI has contributed to particularly over the past 50 years. The subject areas explored in this text include:

- Forest Health – Along with many partners, the company has made significant investments to understand a broad range of forest health issues. Integration of precision forestry tools has supported improved forest management and planning, pest monitoring and managing of insect and disease pressures, as well as the threat of fire.
- Silviculture, Growth and Yield – Trees planted today will grow anywhere from 35-50 years depending on species and site. This requires long-range planning and site-specific strategies which includes understanding of soil and moisture regime conditions. Practices such as site preparation, improved diverse genetics of reforestation stock, vegetation and density management support a growing wood supply and healthy forests. Healthy, growing forests are also the best hedge against the risks associated with changing climates.
- Forest Communities and Landscapes – The Acadian forest comprises a rich mosaic of tree species communities of both ecological and economic value. Soil types, variable climates, landscape and disturbances such as spruce budworm and fire have all played a role in shaping the current composition of our forests. The acquisition and forest management integration of baseline knowledge is critical for maintaining ecosystem health and for tackling future challenges as forest communities adapt to changing climates.

- Biodiversity – Indicators of biodiversity are important measures of forest ecosystem health. The company has made considerable investment to study a diverse set of forest species - from beetles to bryophytes to birds and mammals - to understand how forest management influences these indicator taxa. The science supports the notion that well-managed forests that maintain diverse forest communities across the landscape – from intensively managed stands to conservation areas and everything in between – support a broad array of habitats and forest species.

- Water Quality and Aquatic Habitat – Forests play a vital role in maintaining water quality in streams, rivers and lakes. Aside from providing habitat for aquatic organisms, forest freshwater systems also provide clean drinking water and contribute to flood and drought protection. The company is committed to management practices that maintain high water quality. This has included investments in research to understand the role of managed forests on a broad range of water quality indicators.

- Wildlife Habitat – The company has supported many research projects to understand how animals such as moose, white-tailed deer, American marten, Canada lynx, flying squirrels and others utilize managed forests. These studies identified the varied habitat requirements of each and further illustrates the importance of diverse forest communities across the landscape. Modern enhanced forest inventory tools are being used to model habitat through time to continue to support healthy wildlife populations.

- Hydrology, Soils, and Site Classification – JDI was a partner and collaborator in the development of precision forestry tools related to hydrology and soils. Digital Elevation Models (DEMs) and Wet Area Mapping (WAM) algorithms allow company managers to locate wet areas, including unmapped streams, to both reduce the number of stream crossings and to precisely locate them to minimize the environmental footprint in managed forests. WAM is used extensively in harvesting operations planning to avoid wet areas in harvest blocks to minimize rutting and digital soil classifications systems enable managers to match the right species of seedlings to the right site which improves both the productivity and health of planted stands.

- Climate Change Adaptation and Mitigation – The company has been managing for climate change for decades. Tree improvement strategies have focused on testing genetic material across wide climatic gradients to ensure planted seedlings are well-adapted to a variety of environmental conditions. The unknowns in accurately predicting all climate change-related outcomes are offset by the understanding that proper forest management can mitigate some of the risks. These practices include planting well-adapted seedlings on the right soil types and management of stand densities through thinning in both planted and natural stands. This contributes to healthy forests that are more resilient to climate change stressors. Long-term field test data (both past and present) is a valuable resource in directing action as climate change progresses.

- Carbon sequestration – There is a global focus on the role of forests in mitigating climate change through carbon sequestration. JDI has been involved in assessing the carbon footprint of the company's forest supply chain and related products for over a decade. A rigorous accounting of GHG emissions and removals across the full forest products value chain has been made public and independently certified as net carbon neutral. This work illustrates the key role of managed forests in mitigating climate change.

The knowledge gained from the many decades of forest-related research in these areas has informed company policies, guidelines and the development of best practices. Through the Adaptive Forest Management framework, the company continues to incorporate new information into everyday practice. New technologies that enhance precision forestry capabilities will help drive further improvement into the future. This will have the double effect of also improving conservation measures in the managed forest by enabling a broader landscape perspective and reducing uncertainties related to changing climates.

The purpose of this document is to summarize the research supported by JDI concerning the role of managed forests in conserving biodiversity and to describe how the research is understood and used in company operations. It is not meant to be an exhaustive review of all subject areas. References are provided throughout to assist those wishing to explore topics in more detail.

INTRODUCTION

This document summarizes research and development focused on sustainable forest management that J.D. Irving, Limited (JDI) and many partners have conducted across the region over the past 30 years. It highlights the commitment to land stewardship since the first spruce seedling was planted by the company in northern New Brunswick in 1957, following the massive spruce budworm epidemic in the mid-1950s. Spruce was chosen for reforestation because it is less affected by budworm compared to the more prevalent balsam fir and highlights an early example of incorporating Adaptive Forest Management into company operations. In the last three decades, the Adaptive Forest Management framework evolved to include research to understand and address biodiversity and conservation concerns as knowledge gaps were identified. A hallmark of this approach is the commitment to collaboration and active participation from the broad scientific community involving Federal and Provincial governments, universities, industry and many world-class scientists in specific research efforts. The company has been involved in a number of research collaborations and many are still active today. Examples include the Cooperative Forest Research Unit at the University of Maine, the New Brunswick Growth and Yield Unit, the New Brunswick Tree Improvement Cooperative, the Nova Scotia Tree Improvement Working Group, FPInnovations, SERG International, Fundy Model Forest, Canadian Centres of Excellence – Sustainable Forest Management Network and the Canadian Rivers Institute.

JDI was an early adopter of third-party forest sustainability certification beginning in the late 1990s in the Black Brook forest district due to its long history of forest management. On the recommendation of the certifiers, the company established its Forest Research Advisory Committee (FRAC) to evaluate and improve forest management practices and biodiversity from the stand to the landscape level (MacLean et al., 2010). The group included scientists across a range of disciplines as well as company managers. Scientific Benchmark Reserves (~6,800 hectares) were established in consultation with the World Wildlife Fund (WWF), as well as an additional ~2,600 hectares of Adaptive Management Reserves (AMAs) for the purpose of studying harvesting treatments emulating natural disturbance. These areas have been maintained as reserves for over 20 years and several of the largest ones have recently been entered into the Government of Canada's Protected and Conserved Areas Database as "Other Area-based Conservation Measures" (OECMs).

The collaborative research resulted in benefits to all parties. The company gained new knowledge that helped improve freehold land management, while the projects supported the training of dozens of graduate students at the M.Sc. and Ph.D. levels who have gone on to work in related fields, policy and regulation, or as resource managers. The industry-science partnership structure supports peer review, thus strengthening the science and impact of projects of importance to society, scientific innovation and to the company. Most results are published in peer-reviewed scientific journals. The company has been able to leverage additional resources from various partners and funding agencies to help support the research financially.

Since the 1990s, biodiversity strategies for Crown Land in New Brunswick have focused on preserving viable populations of key vertebrate species representing the biodiversity found in the Province's forests (NB Department of Energy and Resource Development, 2017a,b). These strategies were primarily concerned with conserving natural forests, particularly in mature and over-mature stands. Historically, however, the contributions of managed stands were overlooked due to knowledge gaps in habitat suitability. To help close the gaps, research began in the 1990s with the Fundy Model Forest to evaluate managed forest stands as habitat. This work expanded rapidly in the 2000s through participation in the Sustainable Forest Management Network (SFMN), which culminated in an integrated project titled *'Management implications of forest dynamics, succession, and habitat relationships under differing levels of silviculture'* (MacLean et al., 2010a; MacLean et al., 2010b). This was followed up by a five-year NSERC-supported Collaborative Research and Development project in 2009 to evaluate specific forest stand-level habitat values. The project, titled *'Experimental manipulation of habitat structures in intensively managed spruce planted stands to increase conservation value'*, investigated stand development across a range of treatments, dead wood and coarse woody debris, vascular plant and bryophyte diversity, songbirds, small mammals and beetles (MacLean et al., 2015).

It is well recognized that broader landscape conditions and attributes need to be considered to adequately achieve conservation of biodiversity goals (Higdon et al., 2005; Higdon et al., 2006). To address the landscape perspective, an additional NSERC-supported Collaborative Research and Development project began in 2016, titled *'Landscape-level effects of intensive forest management on biodiversity: integrating monitoring with retrospective and projective landscape analyses.'* The project combined intensive field sampling of specific taxa with traditional forest inventory and state-of-the-art remote sensing forest metrics that enabled the development of landscape-scale habitat models for both current and future forest conditions (Erdozain et al., 2022; Moreau et al., 2022).

The sections that follow describe the scientific research in more detail as it relates to forest management in the context (directly or indirectly) of biodiversity conservation. Emphasis is placed on what is known today but, when appropriate, discussion will include future projections based on changing climates. The subject areas presented include: (a) forest health; (b) silviculture, growth and yield; (c) forest communities and landscapes; (d) biodiversity; (e) water quality and aquatic habitat; (f) wildlife habitat; (g) hydrology, soils and site classification; (h) climate change adaptation and mitigation; and (i) carbon sequestration.

FOREST HEALTH

SPRUCE BUDWORM

Maintenance of forest health is critical to sustainable forest management, both from the standpoint of timber supply and habitat for biodiversity. The most important forest health issue in the region (and across Canada) is the eastern spruce budworm (Gray and MacKinnon, 2006). Budworm epidemics have been cyclic for at least 8,000 years (Miller, 2011), although no substantial defoliation has occurred since the 1990s. Regardless, it is prudent to prepare for the likely return of large-scale infestations.

Research to better understand spruce budworm dynamics was supported by FRAC through participation in the SFMN. The studies developed predictions of forest growth and economic impacts under different levels of budworm infestation severity and compared against different protection strategies (Hennigar et al., 2007; Hennigar et al., 2008a; Hennigar et al., 2013; Colford-Gilks et al., 2012). Specifically, research quantified species-specific impacts of spruce budworm on balsam fir and spruce species. Additional studies assessed spruce budworm impacts on carbon sequestration as concerns around increasing CO_2 levels and climate change emerged (Hennigar et al., 2008b; Hennigar and MacLean, 2010; Neilson et al., 2007; Neilson et al., 2008; Slaney et al., 2009), while other studies focused on the socio-economic impacts of budworm infestations and control options (Chang et al., 2009; Slaney et al., 2010; Chang et al., 2011; Chang et al., 2012). Research was used to develop optimized forest protection strategies.

This research also played an important role in the development of the Atlantic Spruce Budworm Early Intervention Strategy consortium involving the four Atlantic Provinces, the State of Maine, the forest industry (including JDI), Natural Resources Canada, Forest Protection Limited, SERG International and many universities. The Early Intervention program seeks to better understand rising spruce budworm populations and develop early detection and control strategies to keep populations at low levels. Significant investments ($85 million) made in the program from 2014 to 2022 have been successful at keeping budworm populations from reaching outbreak levels (MacLean et al., 2019). This has a positive effect on biodiversity by preserving habitat for organisms dependent on old conifer communities, particularly balsam fir, that may have otherwise succumbed to excessive budworm feeding.

ENDOPHYTE ENHANCEMENT

Over the past 20+ years, JDI, in partnership with Dr. J. David Miller at Carleton University, developed world-first technology to inoculate spruce seedlings with naturally occurring fungi that live inside the needles of trees and produce potent insect toxins (Tanney et al., 2018). This technology, called endophyte enhancement, has been used to inoculate over 250 million seedlings since 2008, which improves the tolerance of the trees to insect attack, primarily the spruce budworm (Quiring et al., 2019a,b; Quiring et al., 2020).

At the national level, introduced pests and diseases are increasingly a major forest health concern. An example is white pine blister rust, which was introduced to North America ca. 1900 and affects all species of five needle pines across the continent and causes enormous damage to valuable pine resources (Livingston et al., 2019). Endophytic fungi isolated from native white pine were identified that produce potent anti-fungal compounds that could be used to improve tree tolerance to fungal diseases (Richardson et al., 2015). The approach of inoculating pine seedlings with endophytes is being explored and could be an important tool to help conserve white pine ecosystems. This is especially timely since a recent decline in white pine health along the Eastern seaboard has been observed due to foliar needle disease thought to be associated with wetter springs (Constanza et al., 2018).

Applications have been developed using native beneficial fungi to improve tree tolerance to insects and diseases.

Native strains of endophytic fungi growing in bioreactors for seedling inoculation to help trees tolerate insect pests.

GENERAL FOREST HEALTH STRATEGIES

Silviculture investments made over the past 50 years have had a positive effect on forest health, especially investments made in reforestation that preferred spruce over balsam fir. Balsam fir is the most heavily budworm-affected tree species. Although spruces vary in susceptibility to spruce budworm, they are generally regarded as less susceptible than balsam fir, where extensive growth losses and mortality occur in fir rich stands in periods of large-scale infestations.

Many forest health issues involve combinations of biotic and abiotic stresses that can be mitigated by making appropriate choices in reforestation. The company has invested significantly in site classification research to aid in silviculture decision making. This is especially important considering the challenges presented by climate change. Planting the right species on the right site, managing competition, and managing densities result in healthier forests that are more resilient to changing climates.

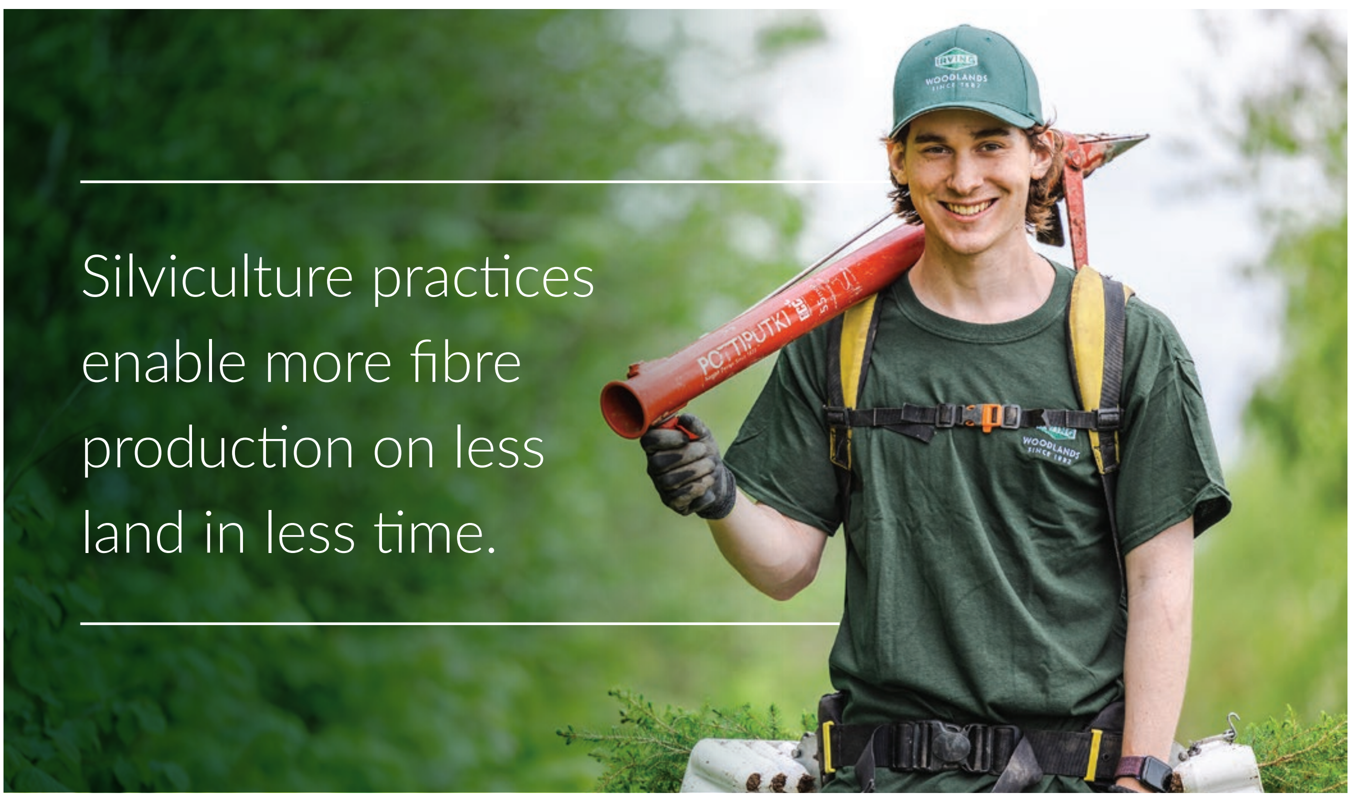
Healthy forests are more resilient forests.

SILVICULTURE, GROWTH AND YIELD

Understanding the effects of silviculture practices on forest growth and yield are critical to sustainable forest management for the broad range of values expected by society. Sustainable harvest levels are determined by describing forest growth through time across all forest types and age classes and then projecting future growth based on current inventory. Our region is at the forefront nationally and internationally in long-range planning and integration with geographic information systems (GIS). This requires extensive R&D and JDI has participated directly in collaborative approaches in New Brunswick through the NB Growth and Yield Unit and with the Cooperative Forest Research Unit at the University of Maine. The company has a large network of growth plots in planted forests due to the long history of planting trees and champions the pursuit of knowledge concerning growth and yield of planted forests. Multi-stakeholder research initiatives are under continuous development to create new regional growth and yield databases and models for managed forests. The company is also at the forefront of integrating on-board Global Positioning Systems (GPS) in combination with GIS on harvesting equipment, aircraft and site preparation equipment to help ensure a high standard of environmental performance.

Silviculture interventions can accelerate the output of forest products through management of tree density and competing vegetation in both naturally regenerated and planted forest stands (Pitt and Lanteigne, 2008; Pelletier and Pitt, 2008). Optimizing the density of trees in a stand dramatically increases the production of forest products relative to undisturbed forest stand development. This is due to allocating more scarce resources (e.g., sunlight, water, and soil nutrients) to fewer trees. However, information on the silviculture of tree species in our region has been incomplete, specifically concerning site preparation methods, optimized seedling quality and establishment, vegetation management and density management in planted stands (Burgess et al., 2010; unpublished reports).

Increasing growth rates through silviculture plays an important role in balancing the need for a competitive forest industry with requirements around conservation of biodiversity and other societal needs. While previous research helped begin to elucidate the habitat value of planted stands for conservation of biodiversity (MacLean et al., 2015), future work will further close remaining knowledge gaps. It is likely that some older planted stands will be useful for species requiring mature to over-mature conifer stands as existing natural stands start to die off through natural succession.



FOREST COMMUNITIES AND LANDSCAPES

The diversity of a forest is determined by geology, climate, past history and forest structure. Structure is made up of stand types, species composition, age-class distribution and within stand structures (e.g., understory vegetation, the mixture of big and small trees and standing and fallen dead trees). Sustainable forest management planning depends on understanding the dynamics of how these elements change through time at the stand level so they can be interpreted across the broader landscape.

> The Acadian forest consists of a rich mosaic of forest communities across the landscape.

The company operates within the Acadian Forest Region, which is considered an ecological transition zone between northern boreal conifers at their southern limits and temperate hardwoods at their northern limits (Taylor et al., 2017). The area is further subdivided into several Ecoregions, which differ in climate, landforms, latitude, elevation and marine influences (Zelazny, 2007). As a result, the forest types and their tree species composition in each ecoregion reflect these natural differences along with historical natural occurrences and human disturbances (Etheridge et al., 2006; Loo et al., 2010; Amos-Binks and MacLean, 2016).

THE EFFECT OF NATURAL DISTURBANCES ACROSS THE LANDSCAPE

Several studies were conducted in the Black Brook district to better understand the interplay of natural and human disturbances at a landscape scale. The studies looked at changes in forest composition from the 1940s to early 2000s and then projected changes into the future based on management plans. The findings showed the percentage of softwood forest remained static over time (40% to 42%), but the species composition changed significantly, with increasing percentages of spruce over balsam fir and the age class composition shifting younger (Etheridge et al., 2005). Changes were also observed in the amount of hardwood and mixedwood forests. Hardwood forests increased (10% to 25%), but at the expense of mixedwood forests (37% to 18%). All three forest classes were projected to remain stable at these levels into the future (Etheridge et al., 2006).

Much of the change in the Black Brook landscape over the decades was due to natural disturbances, primarily spruce budworm epidemic cycles and a decade of birch dieback in the early 1900s. These disturbances resulted in a period of high species turnover and reorganization that lasted for years and varied across stand types (Amos-Binks and MacLean, 2016). The disturbances had the greatest impact on mixedwood forests by altering the proportion of softwood and hardwood tree species in these stands. Mixedwood forests that were dominated by red spruce as the softwood component tended to be more resilient to spruce budworm epidemic cycles and, therefore, lasted longer on the landscape, whereas mixedwood forests dominated by balsam fir as the softwood component was much less resilient to budworm and lasted for shorter periods of time. As the softwood component in mixedwoods stands gradually dropped out, the composition of the stand shifted more to hardwood composition (Amos-Binks et al., 2009; Amos-Binks and MacLean, 2016). The vulnerability of balsam fir to these natural dynamics led to forest management decisions to replace fir with spruce in planted stands and salvage fir in mixedwood stands through selection harvesting.

> Forest communities are dynamic and always changing as a result of natural and human disturbances.

TREE SPECIES DIVERSITY IN THE ACADIAN FOREST

The Acadian forest is often described as a rich mosaic of different types of forests painted across the landscape and is unique in the world for its array of softwood, hardwood and mixedwood stands. These forests are made up of different mixtures of tree species that supports abundant habitat for plant and animal biodiversity.

Responsible forest management depends on a solid understanding of the region's ecology to ensure appropriate habitat conservation for biodiversity. Concern is often raised that forest management reduces tree species diversity and the term "monoculture" is sometimes used without an appreciation for the actual diversity of managed forests. To close this knowledge gap, the company supported an in-depth analysis describing the full diversity of tree species across all the lands it manages in New Brunswick (White et al., 2023). The lands were divided into 21 different forest communities that best describe their makeup based on the predominant tree species, age of the forest and harvest history (if any). Individual trees were counted in sample plots located within each forest community and the amount to tree species diversity was quantified using Hill numbers, which measure species richness, typical species and abundant species (Hill, 1973; Chao et al., 2014; Ohlmann et al., 2019).

The analysis revealed a remarkable degree of tree diversity. JDI-managed lands support 31 different tree species and all forest community types have at least 16 species, with some having as high as 28 species. For instance, species richness in softwood communities (including planted stands) ranges from 18-24, hardwood communities have 19-22 species and mixedwood communities have 22-28 species. Even communities characterized by one or two species still have high overall diversity. These include pine (18-21 species) and cedar communities (22 species). The softwood riparian community, which represents one of the late successional forest types, had the lowest diversity with 16 species represented, despite receiving one of the least amounts of management interventions. This can be explained by hydrology and soils that are typical of riparian areas: fewer species are adapted to tolerate wetter soil conditions. Nevertheless, riparian buffer strips are abundant across the landscape (~47,000 km on JDI-managed lands, totaling an area ~281,000 ha) and are important conservation habitats and provide water protection.

Well-managed forests support considerable tree species diversity.

Species abundance is another measure of diversity in addition to richness. Not surprisingly, the number of abundant species across all the forest community types (ranging from 6-12 species) was less than the total number of species observed (i.e., richness) and reflects the ecology of different species. The study helps to highlight the less common species that may require targeted

conservation measures. These are addressed through company policies, guidelines and best practices such as Forest Species of Concern, Maintaining Late-Successional Forests, Maintaining Vertical Structure, and Maintaining Legacy Trees (Table 1). At the other end of the spectrum are the species in high abundance across the landscape. A surprising result from this study is the overall abundance of balsam fir, which accounts for approximately 31% of all trees over 1 cm diameter at breast height (DBH) on the landscape. Fir is a species not expected to do well under anticipated climate warming scenarios (Taylor et al., 2017; Potter et al., 2017) and its decline could have major impacts on forest composition, biodiversity and forest management plans.

Overall, our analysis suggests that forest management does not reduce the diversity of tree species in the region's forests. In fact, a strong argument can be made that managed forests contribute to biodiversity by maintaining a diversity of forest communities across the landscape (Duflot et al., 2022).

TRIAD FOREST MANAGEMENT

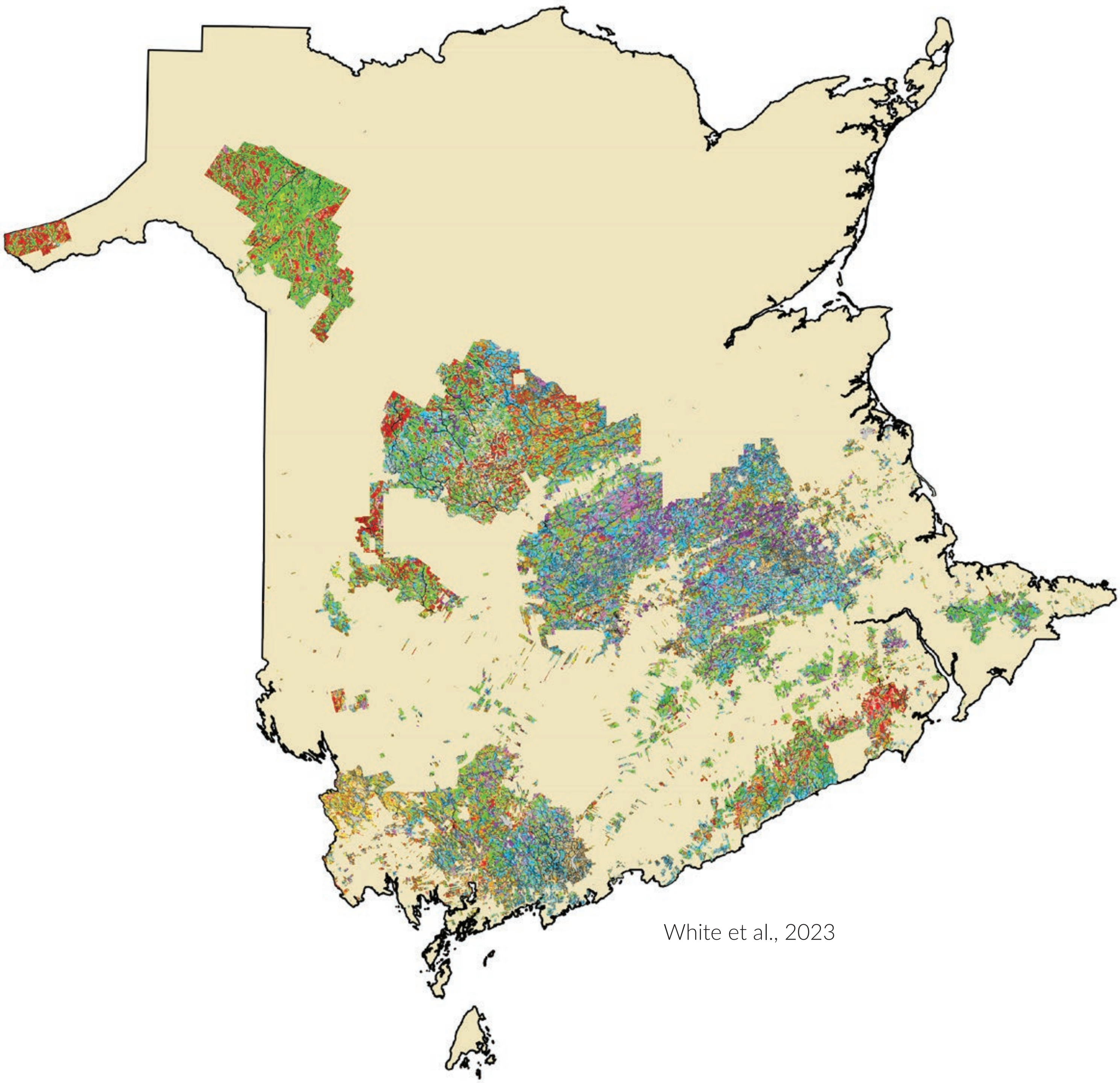
In recent years the concept of Triad forest management has received attention as way to balance the economic and conservation needs across forest landscapes. The practice involves segregating the landscape into three zones: (1) a protected zone for conservation, (2) an intensively managed zone for provision of timber, and (3) a zone consisting of the remaining forest that is managed for multiple purposes based on ecological principles, which often involves management inspired by natural disturbance (Seymour and Hunter, 1992).

Some of the earliest research to evaluate the Triad concept was initiated through FRAC in the Black Brook district. An area of Adaptive Management Reserves was set aside to explore how treatments emulating natural disturbance could be applied at the landscape level (MacLean et al., 2010a). The treatments emulated tree species-specific budworm mortality under different levels of budworm infestation (Montigny and MacLean, 2005, 2006; Ward and Erdle, 2015). Permanent sample plots (PSPs) were established before and after treatments to measure various forest metrics such as growth and biodiversity (Spence and MacLean, 2011; 2012). The same plots will be remeasured in future research to help understand the trade-offs when considering Triad zoning in conifer-dominated forests across the region.

SUMMARY

Results from these studies at the landscape level and previous research are integrated into Adaptive Forest Management planning to strengthen objectives of maintaining diverse forest communities. Actions include: (1) establishing a Unique Areas Program to preserve unique, fine and coarse filter biodiversity; (2) setting target levels for various old forest habitat types; (3) establishment of internal best management practices, guidelines and policies related to preserving biodiversity (refer to Table 1); and (4) continuing research to better understand managed stands (including planted stands) and their contributions to habitat, diversity and other ecological services.

Spatial distribution of 21 forest communities on JDI-managed land in New Brunswick. Each colour represents a unique forest type and age class.



White et al., 2023

BIODIVERSITY

The maintenance of biological diversity from the finer species level to the broader ecosystem level is an integral part of Adaptive Forest Management. Research has focused on understanding the role of managed forests for biological communities and to better understand the effects that forestry practices have on those communities. The scientific approach taken to address these questions is to study taxa that are indicators of forest health such as bryophytes, vascular plants, beetles and birds.

BRYOPHYTES AND VASCULAR PLANTS

Bryophytes (a group which includes liverworts and mosses) are good indicators of forest health because they cannot disperse rapidly and are sensitive to changes in the moisture level of their environment. The Fundy Model Forest and FRAC supported studies in intensively managed forests to better understand how forest management impacts bryophyte communities and showed that their diversity is dynamic and resilient over time. Bryophyte richness initially decreased in managed stands after the early period of disturbance, but soon began to recover as the stand canopy closed. As the stand continued to age, the number of species increased to levels similar or higher than natural stands of similar age (Fenton et al., 2003; Schmalholz et al., 2011).

Although there was no effect on species richness in managed stands, disturbances altered species composition (Fenton et al., 2003). These effects could be mitigated, however, through the retention of remnant canopy patches (i.e., islands) and practices that leave behind fine and course woody debris (Fenton and Frego, 2005; Schmalholz et al., 2011). Utilizing company programs such as Maintaining Vertical Structure and Biomass and Residue help address these concerns. In addition, wetter areas like cedar stands and riparian zones are particularly rich in bryophyte species and help to repopulate harvested areas in the managed landscape (Bourgouin et al., 2022). Harvesting in these areas is restricted through government policies and voluntary programs (Table 1).

Remnant canopy patches (i.e., islands) and retention of woody debris help support abundant bryophyte, vascular plant and beetle communities.

Vascular plant communities followed similar dynamics to bryophyte communities in managed stands. Plant composition in the forest understory of managed forests returned to similar levels as the undisturbed forest, particularly if debris was left on the treatment site (La France and Roberts, 2010; Haughian and Frego, 2016). This further highlights the importance of leaving fine and coarse woody debris in place to facilitate recovery of disturbance-sensitive species (Haughian and Frego, 2016).

BEETLES

Beetles are important contributors to nutrient cycling and energy flows in ecosystems (Nadeau et al., 2015b). The company supported a number of studies which examined the effects of commercial thinning strategies on beetle communities in managed stands. The studies showed that commercially thinned stands have levels of beetle abundance and richness equal or higher than old conifer forests (Nadeau et al., 2015a). Like bryophytes and vascular plants, beetle communities are also dynamic and are supported by the retention of woody debris and standing dead wood (Nadeau et al., 2015a; Thibault and Moreau, 2016a,b). Studies showed that beetle species abundance and richness increased rapidly soon after harvest, helping to recycle nutrients in the dead woody debris, and then declined as the debris decayed (Gandiaga and Moreau, 2016a,b). In a further study, Chiasson and Moreau (2021) demonstrated the effectiveness of remnant canopy patches (i.e., islands) for conservation of species abundance and richness within a harvested area. Taken together, these studies indicate that well-managed forests support diverse beetle communities (Moreau et al., 2022).

BIRDS

Birds are arguably the most intensively studied taxa in the world. There has been an immense amount of data collected over the past two centuries that has allowed the scientific community to assess population trends over time. In North America, the slow decline of many bird species has been well documented and attributed in part to the loss of critical habitat (North American Bird Conservation Initiative, 2022; The State of Canada's Birds, 2019). For those species that breed in forests, it is important for land managers and conservation specialists to understand the role managed forests play in supporting their habitat needs.

Well-managed forests support many species of birds.

Studies at the stand level

The company participated in studies that examined the role of managed forests at the stand level, which included studies of bird richness and abundance in planted stands and stands that have undergone a recent harvest treatment. The studies showed that managed forests provide important habitat for many bird species that prefer spruce and fir forests, tall canopies, forest edges or are otherwise generalists in their habitat preferences (Guénette and Villard, 2005; Keppie et al., 2006; MacKay et al., 2014; Rolek et al., 2018). Moreover, forest management practices that promote uneven age classes and young spruce-fir forests help stem the decline of species that prefer these forest communities (Rolek et al., 2018).

However, some bird species are more sensitive to disturbances. These tend to be species that occupy specific niches that offer specialized structures for nesting and/or feeding, so it is important that specific attention be paid to them to ensure their habitat needs are maintained (Guénette and Villard, 2005; MacKay et al., 2014). Studies were conducted in the forests of Black Brook to better understand the role of managed forests to support species requiring specific habitats. The studies focused on three species with different needs but are generally representative of birds that could be most impacted by forest management practices. Information learned from studying these species can then be applied to other sensitive species with similar habitat requirements.

> Forestry policies, practices and programs help address the needs of bird species requiring special considerations.

The first species studied was the Brown Creeper (Certhia americana). It is a small (5.25 inches in length), non-migratory resident that has an affinity for large trees. They like to scavenge for insects by working a tree from the bottom to the top, spiraling their way around the trunk as they go. They feed by using a long, curved bill to probe crevices in the bark and prefer to build their nests behind pieces of peeling bark from snags and declining trees. Ornithologists classify them as an old forest-associated species since this forest type has an abundance of large dead and dying trees, so they are sensitive to forest management practices that reduce it. Indeed, studies showed a decline in Brown Creeper abundance after partial harvest, mainly due to a reduction in quality trees for finding food (Poulin et al., 2010; D'Astous and Villard, 2012). These findings helped build models to determine the size and density of large dead trees needed to support populations at the stand level (Guénette and Villard, 2004; Poulin et al., 2008).

The second species studied was the Ovenbird (Seiurus aurocapilla), a small (6.0 inches in length) migratory species and a member of the warbler family. They generally breed in old deciduous or mixedwood forests and prefer stands with a relatively closed canopy and deep leaf litter. They use old leaves to build their nests on the forest floor in the shape of a dome resembling an old-fashioned oven, hence its name. Since they prefer forests with a closed canopy cover it was expected they would be sensitive to management practices that created more open canopy. Studies were carried out to measure Ovenbird densities following partial harvest treatments (Pérot and Villard, 2008; Thériault et al., 2012). Although densities were lower in stands early after treatment, populations increased as the canopy closed such that by the fifth year following harvest no effect could be detected (Haché and

Villard, 2010; Haché et al., 2013; Villard et al., 2012). In the case of Ovenbirds, habitat modelling determined that climate change is projected to have a greater impact on population dynamics than forestry practices (Haché et al., 2016).

The third species studied was the Pileated Woodpecker (Dryocopus pileatus), a crow-sized (16.5 inches in length), year-round resident. Their preferred food is carpenter ants and other insects that feed in dead trees. Consequently, Pileated Woodpeckers are associated with mature and old forests where there is an abundance of large dead and dying trees that supports their primary source of food. They excavate large cavities when they forage that become future nesting sites and shelters for other bird species and woodland animals, making these woodpeckers important species for healthy, functioning forest ecosystems. Work conducted in Black Brook reinforced the importance of large dead trees and proposed threshold numbers for dead trees at the stand level to support healthy woodpecker populations (Guénette and Villard, 2005; Lemaître and Villard, 2005; MacKay et al., 2014).

Studies at the landscape level

While many important insights were learned for birds at the stand level, it follows to study the effects of forest management at the landscape scale. Birds are highly mobile, so the broader spatial forest context needed to be taken into account (Poulin and Villard, 2011; Villard and Hache, 2012).

Research was conducted over three years to address the landscape question by monitoring birds within different forest communities in landscapes of varying forest management intensity. If intensive forest management had an effect on birds at a landscape level, then differences in their populations should be observed compared to their populations in the less intensive landscapes. Autonomous Recording Units (ARUs) were installed in replicated mature forest communities in each of the three landscapes that recorded birds singing at various times throughout the day. Experts then listened to the recordings to identify individual species (richness) and the relative number of each (abundance). Analysis of data from the recordings showed that richness and abundance of birds was the same (or slightly higher) in the intensively managed landscape compared to the less intensive ones, and supports the conclusion that, at a landscape scale, intensively managed forests provide important habitat for birds (Venier et al., 2023).

> Intensively-managed landscapes provide important habitat for birds.

The study also provided useful information for two species at risk, the Canada Warbler and Olive-sided Flycatcher. ARUs placed in a variety of different forest communities revealed a clear picture of which communities each species used, which then enabled habitat models to be developed based on the occupancy data (Remus et al., 2023). Scaling the models across the entire study area showed that the managed forests of Black Brook support important levels of habitat for both species. Future work will be aimed at developing habitat models for other bird species or groups of species present in the district and projecting those models into the future based on management plans and other scenarios like climate change.

SUMMARY

Research on bryophytes, vascular plants, beetles and birds demonstrates that well-managed forests with a diversity of forest types and age classes across the landscape and diverse forest structure within them support a broad range of species. While managed forests are well-suited for many species, the research emphasized the needs of some species require extra consideration. Company policies and programs such as Forest Species of Concern, Wetland Buffer Zone standards, Late-successional Forest standards, Rare Plant Pre-screening program, Maintenance of Vertical Structure policy, Legacy Tree program, Vernal Pools policy, Raptor and Heron Stick Nest policy, and Biomass and Residue Utilization policy, help address those needs (Table 1).

WATER QUALITY AND AQUATIC HABITAT

WATER QUALITY ASSESSMENTS

Forests are vital to maintaining aquatic system integrity which, in turn, provides ecological services like clean drinking water, flood and drought protection and biodiversity. A series of studies were recently conducted to better understand the effects of forest management on indicators of water quality, such as abiotic factors (e.g., water temperature, sediments, water chemistry, leaf litter decomposition and mercury levels) and biotic factors (e.g., algae and biofilm, macroinvertebrates and sculpins) under the influence of varying levels of forest management intensity (i.e., minimal, extensive and intensive) (Erdozain et al., 2022).

The studies found that in forest headwater streams, more intensive levels of forest management have a modest impact on abiotic water quality indicators and those effects accumulate from upstream to downstream river systems (Erdozain et al., 2018; Erdozain et al., 2021a,b). Harvest practices (i.e., clearcutting and selection harvesting) do not appear to be the primary contributing factor for these modest changes, but rather the density and location of road crossings. Poorly constructed or legacy forest road infrastructure can act as conduits to deliver sediments containing inorganic and organic terrestrial materials to aquatic systems, including mercury (Erdozain et al., 2019; Negrazis et al., 2022). Further, poorly constructed roads can cause fragmentation of aquatic ecosystems contributing to a disruption in connectivity (Arsenault et al., 2022).

Forest roads and water crossings have the greatest impact on water quality.

Sedimentation from poor road construction altered food web dynamics whereby the biotic component of aquatic systems tended to rely more on lower quality terrestrial food sources rather than higher quality aquatic food sources (Erdozain et al., 2019). This could have negative implications for higher trophic levels and stream functions like nutrient cycling (Erdozain et al., 2022). However, the effects of forest management on the abiotic component do not appear to have an accompanying effect on the biotic component. While a slight reduction in abundance of macroinvertebrates was measured, no other biological impacts were observed, which suggests that current management best practices protect aquatic biological integrity (Erdozain et al., 2021c). Given the large network of roads and culverts in managed forests, coupled with the potential to impact aquatic systems, it is important that this infrastructure is assessed periodically. New remote sensing tools have been developed to make this more feasible and to enable forest managers to prioritize potential problem areas (Arsenault et al., 2022). For well over a decade, Wet Areas Mapping (WAM) has been employed across all operations in new road construction and maintenance to reduce the number of water crossings required and to inform maintenance plans to minimize potential impacts on water quality.

RIPARIAN BUFFER ZONES

Riparian zones in forested areas serve crucial functions to conserve water quality. These services include maintaining stream banks, storing floodwater, trapping sediments, filtering nutrients and shading streams to reduce solar heat gain. Several policies and best practices are in place to direct forest managers how to operate in these sensitive areas to ensure high environmental standards are maintained (Table 1). A recent assessment supports that current best practices are meeting the objectives (Erdozain et al., 2020). However, the current best practice of fixed width buffer zones may not be wide enough to include all surrounding wet areas and could lead to higher stream water temperatures due less shading and warmer groundwater. It was recommended that management practices consider variable width buffers that encompass these hydrologically connected areas (Erdozain et al., 2020). Elevated water temperatures are detrimental to fish, yet these studies showed that temperatures were well below these threshold levels in managed forests (Erdozain et. al., 2018).

FISH HABITAT

Additional studies were conducted to better understand fish habitat requirements at both the finer and landscape scales. This work employed thermal infrared imagery technology to identify cold water refugia in streams and rivers (Monk et al., 2013; Wilbur et al., 2020). Cold water refugia are critical aquatic habitats for species that thrive in cooler water, such as salmon and brook trout. Fish seek out these refugia during periods of elevated temperature stress. Further research then characterized landscape and geological features that contribute to maintaining and enhancing these habitats (O'Sullivan et al., 2019; 2020; 2021). The aim is to have readily available tools and information to assist forest managers in identifying critical aquatic habitat areas requiring extra care and attention.

SUMMARY

Overall, these studies reveal the strong interconnectedness of aquatic systems to their surrounding landscapes by water (O'Sullivan et al., 2022). Forest management practices directed at minimizing ground disturbances in areas with direct hydrological connections to streams and reducing dissolved and particulate matter inputs from roads and stream crossings are effective at preserving ecologically sensitive aquatic habitats (Erdozain et al., 2019).

Precision forestry tools, such as Wet Area Mapping, riparian buffer zone management and remote sensing tools are used to protect water quality and fish habitat.

WILDLIFE HABITAT

Responsible forest management shares an obligation to not only meet timber objectives but to ensure conservation of sufficient habitat to support a variety of keystone wildlife species. Several studies conducted (and ongoing) in recent years have sought to better understand the impact of forest management on diverse vertebrate species, including iconic species such as white-tailed deer and moose.

WHITE-TAILED DEER

A multi-year study is underway on white-tailed deer, aimed at better understanding the impacts of intensive forestry on habitat selection, survival and population growth. This will include a snow model for predicting the impact of winter snow depth, a food model for predicting energy content of vegetation and resource selection functions for summer and winter ranges. The objective is to build an overall model to predict long-term population change in relation to availability and distribution of critical habitat that may be impacted by forestry practices. While much of this work is ongoing, preliminary analysis indicates summer ranges contain an abundance of vegetation within reach of deer, and that they prefer stands with canopy heights less than 12 m. In the wintertime, deer prefer ranges that are dominated by dense mature conifer forests that intercept snow and provide cover from severe weather and predators. Winter ranges, however, are influenced heavily by illegal feeding stations that place the population at risk of communicable diseases (P. Wiebe, unpublished).

> Well-managed forests support habitat for many mammal species.

MOOSE

The moose population in eastern Canada is at the southern range of its native habitat and is increasingly subject to the impacts of climate change due to increasing abundance of winter ticks, which have a severe negative impact on moose body condition (Deb et al., 2020). A multi-year study is working to assess moose body condition, habitat structure and environmental factors on the intensity of winter tick infestation (www.albipictus.com). The study will investigate if forestry management practices can help mitigate winter tick densities and/or moose-tick encounters.

AMERICAN MARTEN

American marten is associated with old coniferous forests, and therefore thought to be vulnerable to intensive forest management that reduces the amount of this forest type across the landscape. To answer this question, a multi-year study assessed whether managed forests provide suitable habitat by measuring marten abundance and fitness in planted stands of varying age classes. The study found that conifer stands 20+ years old offer abundant habitat for cover and foraging opportunities, so long as they cover no more than 50% of the landscape within the marten's defined ranges. This is because they require large snags for maternal denning sites that are typically present in mature natural stands but are less abundant in planted stands (Forget et al., 2010).

CANADA LYNX

The Canada lynx is listed as a threatened species in the United States and an endangered species in New Brunswick and Nova Scotia (Hoving et al., 2005). These listings necessitated the need for multi-scale studies to better understand lynx habitat requirements. Research showed that lynx prefer habitat that has high annual snowfall and intermediate coniferous canopy cover that support abundant populations of their primary food source, the snowshoe hare (Fuller et al., 2007; Fuller and Harrison, 2010). Their preferred habitat tends to be stands dominated by conifers approximately in the 15–35-year age class following clearcut harvesting (Simonds-Legaard et al., 2013). These studies clearly support the link that current forest management practices that promote abundant hare habitat also support lynx populations (Olson and Harrison et al., 2014). The greatest threat to lynx is climate change that will reduce snow cover below critical levels in its southern range (Simons-Legaard et al., 2016).

FLYING SQUIRREL

The flying squirrel is a species presumed to be affected by fragmentation of the landscape between young and mature forest habitat. A four-year study conducted in an intensively managed forest, however, found that flying squirrel abundance was similar in fragmented and contiguous landscapes, suggesting that they are better able to utilize young forests than previously thought (Smith et al., 2010).

SMALL MAMMALS

Several multi-year studies investigated the effects of pre-commercially thinned mature stands and plantation on population dynamics of small mammals such as voles and shrews. While results varied by year and study type, in general, these stands maintained abundant populations of small mammals so long as sufficient supply of fine and coarse woody debris was retained after harvest (Keppie et al., 2006; Henderson and Forbes, 2010; Dracup et al., 2015).

SUMMARY

These studies demonstrate that well-managed forests, with a diversity of habitats at the landscape level, support abundant habitat for many wildlife species. This is supported by a study that looked at the potential risk of extirpation of 157 species in an intensively managed forest and found that 26 were rated most at risk (Higdon et al., 2005). The reason was due primarily to the loss of mixedwood habitat and habitat fragmentation without sufficient connectivity, based on the available knowledge of habitat requirements at the time (Hidgon et al., 2006). To mitigate the risk of extirpation of this subset of species, the authors recommended (i) providing for future mixedwood habitat, (ii) decreasing the trend toward smaller patch sizes, and (iii) increasing the connectivity of habitat patches for dispersal-limited species. Even with appropriate mitigation measures in place, some species in their more southern ranges, like American marten and moose, are expected to do poorly because of climate change (Deb et al., 2020).

HYDROLOGY, SOILS AND SITE CLASSIFICATION

WET AREAS MAPPING

Hydrology and soils are critical drivers of the diverse ecology across the region. Prior to 2000, there were several soil map and topographic information resources available such as soil surveys and ecological land classifications (Pitty 1979; Moore et al., 1993; Zhu and Mackay, 2001; Odgers et al., 2014; Furze et al., 2017a); however, they were limited in precision and not widely used in forestry applications. In the early 2000s, JDI began a research collaboration with Dr. Paul Arp of the Watershed Research Centre at the University of New Brunswick to evaluate new Wet Areas Mapping (WAM) algorithms and techniques. Methodology developed by Dr. Arp and his team was highly accurate for mapping wet areas across the landscape, including unmapped streams (Murphy et al., 2007, 2008). This tool proved to be immensely valuable in helping the company meet or exceed water protection standards across all forest operations.

The accuracy of WAM is dependent on the precision of topographic digital elevation models (DEMs) and, together with the WAM algorithms, have been substantially improved in the last two decades. More recently, complete coverage of New Brunswick with LiDAR (Light Detection and Ranging) has improved DEMs to sub-meter accuracy. Apart from improving environmental performance in terms of protecting water quality and aquatic habitat, wet areas are important for a range of terrestrial and semi-terrestrial organisms such as bryophytes and amphibians (Bourgouin et al., 2022; National Research Council, 1995). WAM is now fully integrated into all levels of company forest planning and operations, like computer screens onboard harvesting equipment to help the harvesting operator avoid wet areas. Next-generation tools assist in planning related to road location, maintenance and harvest block layout,

> Precision forestry tools, such as Wet Areas Mapping and Digital Soils Maps, improve forest productivity and environmental performance.

which improves both environmental performance (i.e., reduced rutting) and efficiency (Jones et al., 2018; Vega-Nieva et al., 2009).

DIGITAL SOILS MAPS

Hydrology, soil type, soil depth and topographic position have a critical influence on forest communities. A project with Dr. Arp and the Watershed Research Centre resulted in combining all the different soil survey and mapping information developed over prior decades with WAM to improve site classification and forest productivity mapping (Furze et al., 2017; Furze, 2018). These new digital soils maps are used to help inform forest management decisions, such as making the most appropriate harvesting prescriptions and determining the best silviculture interventions for both natural regeneration and planted stand establishment. The same information is equally useful for conservation planning.

FLOODING IN WATERSHEDS

There is growing concern around more frequent extreme climate change-related weather events. Several major rainfalls in recent years caused flooding in our region that led to damage to infrastructure and the environment. For managed forests specifically, there is concern around the amount of harvesting in watersheds and whether it exacerbates flooding risk. The company used metrics developed in Quebec (Langevin and Plamondon, 2004) to assess watersheds across JDI-managed land with respect to harvesting and flooding risk. Preliminary analysis of Clearcut Equivalent Watershed Percentages has shown that harvesting activities across the landscape on JDI-managed forests has not exceeded levels where the probability of observing an increase in peak flows sufficiently large to alter aquatic habitat has been reached. Work is continuing in this area through the Canadian Rivers Institute at the University of New Brunswick.

Clearcut Equivalent Watershed Percentages are used to define the amount of tree removal in a watershed over a particular time to mitigate flood risk.

CLIMATE CHANGE ADAPTATION AND MITIGATION

JDI has long been aware of the challenges associated with climate change and the importance of adaptation and mitigation efforts (Canada. National Roundtable on the Environment and the Economy, 2012). Significant public investment on Crown land and private investment on Freehold land through planting trees and pre-commercial thinning of natural regeneration has had (and will have) a long-term positive impact on managing risk at the landscape level. Both interventions improve stand health and shorten rotation ages, which directly reduces the period of risk.

IMPLICATIONS TO FOREST HEALTH

Projections of climate change across the region indicate more intense weather events and more frequent interactions with insect and disease conditions, including invasive species (Hushaw et al., 2018). Planted stand establishment, pre-commercial and commercial thinning are silviculture strategies that play important roles in adaptation of managed forests. From an adaptation standpoint, managing the density of trees through thinning reduces competition of remaining trees for water, nutrients and sunlight. This results in greater crown area on individual trees, more rapid growth and better overall stand health, which in turn reduces the impact of abiotic and biotic stresses (Moreau et al., 2022).

A ROLE FOR SILVICULTURE AND SPECIES SELECTION IN ADAPTATION STRATEGIES

Planting trees and pre-commercial thinning also provide opportunities to adjust the species composition of stands. This favours native species predicted to fare better in warming climates (Taylor et al., 2017) and plays an important role in conservation of biodiversity by increasing the prevalence of more resilient species like white pine and red spruce (Potter et al., 2017). Conversely, balsam fir is the most common tree species across the region but is not predicted to do well as climates warm (Vaughn et al., 2021). Already we are seeing extensive mortality of the species in southern New Brunswick. This is partially associated with attack by balsam woody adelgid, a non-native insect species favoured by a warming climate (Greenbank, 1970). As old balsam fir disappear this will ultimately impact habitat of species requiring old conifer forests, so silviculture treatments that favour longer-lived conifers are desirable.

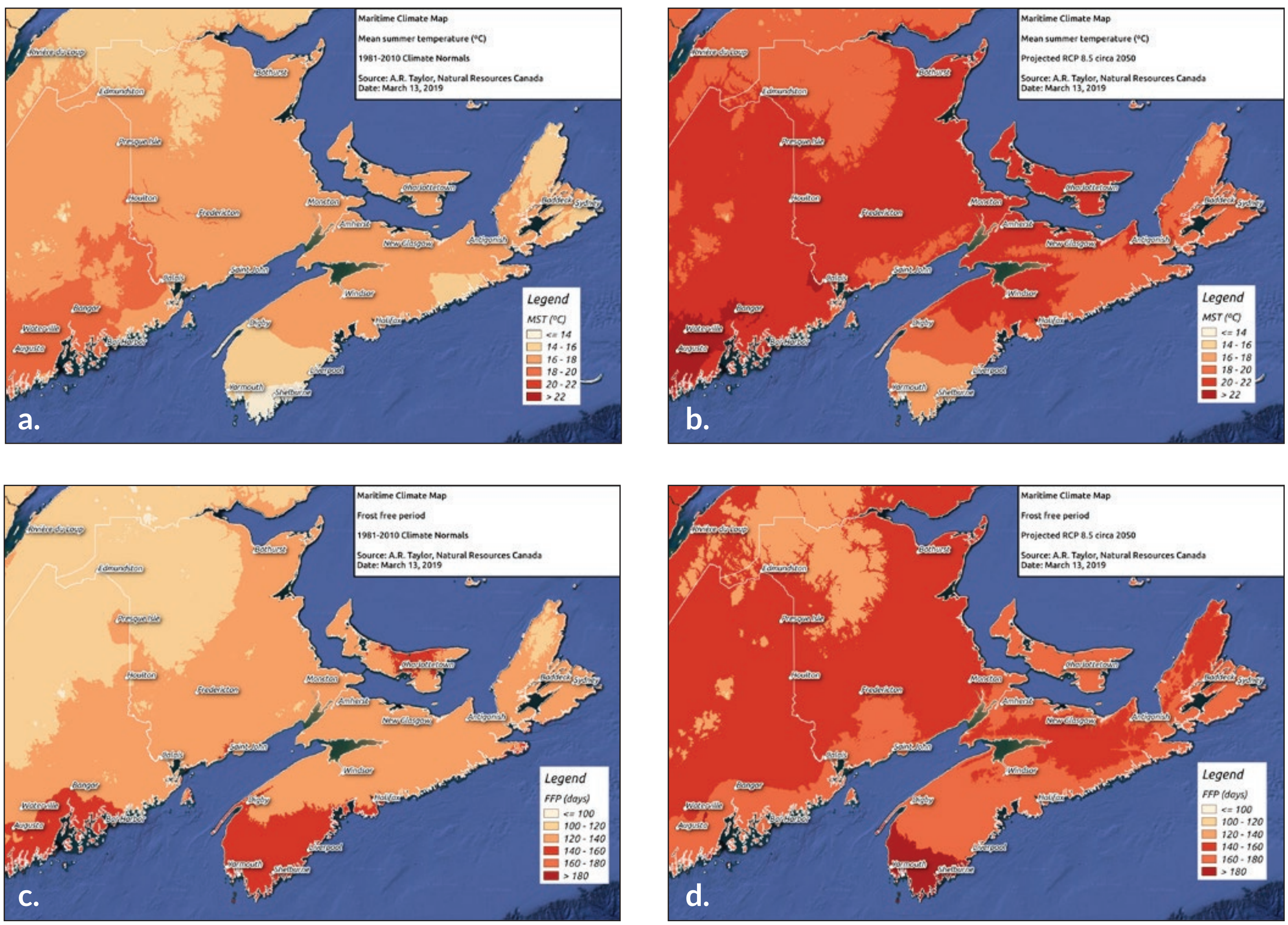
Improvements in silviculture practices, particularly within planted stands, will help to further mitigate risk. Advances in soils and site classification (see previous section) are resulting in more refined prescriptions in species selection, site preparation, vegetation management and overall density management. Optimal species selection and density management will improve resistance to changing climate stressors, both abiotic and biotic. As climates change, tree planting will be required for assisted migration strategies, such as the introduction of non-local seed sources of native species or of species not currently present on the landscape (Ste-Marie et al., 2011).

A ROLE FOR TREE IMPROVEMENT IN ADAPTATION STRATEGIES

Investments in tree improvement have been critical given the overall investment in reforestation. This research involves selecting the best quality trees in the forest, establishing seed orchards by grafting, breeding the best parents and field testing. Overall objectives are to increase the value of planted forests and maintain broad genetic diversity from an adaptation standpoint. Seedlings planted from the early 1990s to present-day grow between 10-25% faster than trees originating from unimproved wild stand collections (Ye, 2020; 2021). Improvements to quality traits such as tree straightness are also well-documented (Weng et al., 2015).

Sustained collaborative R&D initiatives involving provincial governments, universities, Natural Resources Canada and forest industries have put the region in a leading role nationally for tree improvement. A broad range of conifer species are included in tree improvement programs, including white, black, red and Norway spruces, white pine, jack pine and eastern larch. Field testing associated with tree improvement has been conducted across a broad geographic range in New Brunswick and

Nova Scotia (approximately 3 deg latitude and 4 deg longitude). This region also represents a wide climatic gradient of up to 75 frost-free days per year and a range of winter extremes. Current environmental gradients of our region are already greater than the forecast changes projected for the next several decades (Climate Atlas of Canada). Parents selected for tree improvement programs of any of the spruces have demonstrated stability across a range of environments, which bodes well for their adaptation to changes in the next four decades, particularly for the northern two-thirds of New Brunswick. Recent research on white spruce has demonstrated that selection for greater growth rate will also improve drought resistance (Schortemeyer, 2022). As the climate changes, more southerly sources of native species may be better adapted, and testing is currently underway with some of these, along with local sources (Atlantic Tree Improvement Council, 2022). Recent advances in molecular genetic non-GMO technology like genomic selection hold promise to speed up the testing process in combination with traditional long-term field testing (Beaulieu et al., 2020).



Projected increases to summer temperatures (a-b) and frost free periods (c-d) in the Maritime provinces by 2050 due to climate change.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CARBON SEQUESTRATION

Forests have a role in mitigating climate change by absorbing carbon dioxide from the atmosphere and storing carbon in wood. JDI has been involved in R&D related to evaluating forest carbon and assessing the company's carbon footprint over the past decade. Collaborative research with the University of New Brunswick culminated in a comprehensive carbon accounting exercise modeled over the long-term (Cameron et al., 2013). All company sequestration and emissions were modeled, including carbon stored in the forest, emissions related to forest products production and sequestration in forest products and waste streams. Under current conditions, company forests, operations and products are forecasted to sequester over one million tonnes of carbon dioxide equivalents per year over the next 50 years. This represents a positive contribution to reducing greenhouse gases in the atmosphere, and JDI has adopted carbon sequestration modelling as part of the ongoing management planning process. The JDI Forest Supply Chain Carbon Footprint was calculated and independently audited according to the international standard PAS2060:2014. In 2022, the company's forest supply chain was found to remove more CO_2e than it emits by over 1.2 million tonnes. (J.D. Irving, Limited, 2022, Forest Supply Chain, Environment, Social and Governance Report).

Healthy, growing forests are significant carbon sinks.

WELL-MANAGED, DIVERSE FOREST COMMUNITIES ARE HEALTHIER, MORE RESILIENT AND SUPPORT BROAD BIODIVERSITY.

CONCLUSION

J.D. Irving, Limited has strived to manage the forests in which it operates responsibly for over 140 years. This responsibility encompasses many facets: a responsibility to the business, to its customers, to its employees, to the communities where it operates and to the environment. Although this document focuses primarily on the responsibility to the environment, discussions are made with all the other responsibilities in mind, because the company would not operate sustainability without care and attention to all of them.

The Acadian Forest Region where we live is remarkably diverse because of its geology, terrain, climate, hydrology, soils and proximity to the Atlantic Ocean. Yet forests in the region are not static entities. Wind, fire, insects, diseases and human disturbance have shaped the forest for hundreds of years, establishing a rich mosaic of forest communities and a broad range of biodiversity across the landscape. The body of research supported by JDI over the years establishes that well-managed forests augment this biodiversity by promoting different forest types and age classes. Some sensitive species and habitats require special attention, and this is addressed through both legislated and voluntary policies, guidelines and best practices which evolve as new knowledge is incorporated into forest management (documented in Table 1).

As we move into an era of climate uncertainty, the role of managed forests in helping mitigate those effects is increasing in importance. Investments in tree planting and silviculture promote a growing wood supply. These in turn lead to healthier forest stands that are more resilient to changing climates and are important sinks for sequestering carbon. Advancements in precision forestry tools will grow our capability to manage for healthy forests in the future.

Since the establishment of the Forest Research Advisory Committee in the late 1990s, the company has benefitted from the perspectives and knowledge of expert members to proactively understand and develop strategies to improve forest practices. Learnings achieved through research and development are integrated into forest management plans through a framework of Adaptive Forest Management. This scientific approach strengthens the decision-making process and enables a pathway for continuous learning and improvement to meet all the company's responsibilities. While the work remains on-going, the rich legacy of science to date demonstrates how well-managed forests provide for society's needs in a responsible and lasting way.

TABLE 1: LIST OF J.D. IRVING WOODLANDS POLICIES, GUIDELINES & BEST PRACTICES

Document Name	Document Type	Description
Unique Areas Program	Program	A voluntary program used to identify, catalogue, and track special forest lands where the primary management objective is conservation. These sites comprise unique features that make them prized for wildlife, biodiversity, geological, historical, or cultural values. Sites are recorded in the company's GIS database.
Temporary Crossing Installation & Removal	Guideline	A comprehensive set of guidelines and procedures for the installation and removal of temporary water crossings depending on the activity being conducted in managed forests. These procedures ensure water quality and aquatic habitats are protected.
Harvesting On Soft Ground	Best Practices	A comprehensive set of best practices for operating in wet areas to minimize rutting and impacts to soil, watercourses, and aquatic habitat.
Forest Species of Concern	Best Practices	A comprehensive set of best practices for mitigating the impacts to many plant and animal species of concern in managed forests.
Water Course & Wetland Buffer Zone Standards for Forestry Operations	Best Practices	A comprehensive set of best practices for operating near watercourses and wetland buffers in managed forests. These buffered areas are also commonly known as 'riparian zones,' and are important habitat features maintained to protect water quality and habitat for diverse taxa.
Clearcut and Planted Stand Establishment	Best Practices	A comprehensive set of best practices for clearcut harvesting prescriptions and regeneration of forestry stock following harvest, to ensure well-stocked and healthy managed forest establishment.
Planted Stand Cleaning, Pre-Commercial Thinning, & Commercial Thinning	Best Practices	A comprehensive set of best practices for cleaning and thinning planted stands at various rotation ages. These practices reduce competition and tree densities, which promote the vigor, health, and resiliency of planted forests.

Document Name	Document Type	Description
Managing Deer Wintering Areas	Policy	A policy to identify and conserve Deer Wintering Areas (DWAs) in managed forests. DWAs are areas of forest cover where deer congregate in the winter for shelter and are critical winter habitats for supporting healthy deer populations. The policy describes specific best practices for maintaining DWAs and the location of each is recorded in the company's GIS database.
Maintaining Late-Successional Forests	Policy	A policy to maintain a proportion of long-lived stand types across managed lands. These stands include old tolerant hardwood, old tolerant mixedwood, old cedar, old pine & hemlock, and old softwood stands, and are maintained in the company's GIS database. Together, these late-successional forests provide important habitat for many plant and animal species.
Rare Plant Pre-Screening	Policy	A policy to identify and protect rare plants in managed forests. Company Foresters receive training from the company Naturalist on rare plant habitat and species identification. When a rare plant is identified, measures are implemented to protect the site and the location is recorded in the Unique Areas Program.
Control Invasive Woodland Species	Policy	A policy to identify, mitigate and manage invasive species in managed forests. Efforts are made to eradicate or control invasive species when appropriate.
Maintaining Vertical Structure (Islands)	Policy	A policy to retain vertical structure in managed forests where most of the overstory is removed. These vertical retention areas are often referred to as 'islands,' and are maintained across the landscape to preserve special habitat features and provide a source of propagules for nearby regenerating forests. The policy describes specific criteria for retention area size, composition, and location.

Document Name	Document Type	Description
Maintaining Legacy Trees	Policy	A policy to identify and retain outstanding, live, and rare individual trees in managed forests. These trees provide important wildlife habitat and have high conservation value. The company offers a reward program for identification of legacy trees and their locations are recorded in an internal database.
Maintaining Significant Vernal Pools	Policy	A policy to identify and protect significant vernal pools in managed forests. Vernal pools are naturally occurring, shallow, and ephemeral bodies of water in forests that provide important habitat for many plant and animal species. The policy describes best practices for maintaining vernal pools and the location of each is recorded in the Unique Areas Program.
Protection of Raptor & Heron Stick Nests	Policy	A policy to identify and protect nest sites for raptors and herons. Upon identification of a nest site, the bird species occupying the nest is identified and an appropriately sized buffer is placed around the location. The location of the site is then recorded in the Unique Areas Program.
Biomass and Residue Utilization	Policy	A policy to guide decision making when utilizing biomass and other residues from harvesting operations. The directive describes when, where and how biomass may be removed from harvested areas and when it must remain on site so as not to impact important wildlife and aquatic features.

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REFERENCES

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Amos-Binks, L.J., MacLean, D.A. 2016. The influence of natural disturbances on developmental patterns in Acadian mixedwood forests from 1946 to 2008. *Dendrochronologia* 37, 9-16.

Amos-Binks, L.J., MacLean, D.A., Wilson, J.S., Wagner, R.G. 2009. Temporal changes in species composition of mixedwood stands in northwest New Brunswick: 1946-2008. *Canadian Journal of Forest Research* 40, 1-12.

Arsenault, M., O'Sullivan, A.M., Ogilvie, J., Gillis, C-A., Linnansaari, T., Curry, R.A. 2022. Remote sensing framework details riverscape connectivity fragmentation and fish passability in a forested landscape. *Journal of Ecohydraulics* 1-12.

Atlantic Tree Improvement Council. 2022. Establishment Report #3. Fredericton, New Brunswick, Canada.

Beaulieu, J., Nadeau, S., Ding, C., Celedon, J.M., Azaiez, A., Ritland, C., Laverdière, J-P., Deslauriers, M., Adams, G., Fullarton, M., Bohlmann, J., Lenz, P., Bousquet, J. 2020. Genomic selection for resistance to spruce budworm in white spruce and relationships with growth and wood quality traits. *Evolutionary Applications* 13, 2704-2722.

Bourgouin, M., Valeria, O., Fenton, N.J. 2022. Predictive mapping of bryophyte diversity associated with mature forests using LiDAR-derived indices in a strongly managed landscape. *Ecological Indicators* 136, 108585.

Burgess, D., Adams, G., Needham, T., Robinson, C., Gagnon, R. 2010. Early development of planted spruce and pine after scarification, fertilization and herbicide treatments in New Brunswick. *The Forestry Chronicle* 86, 444-454.

Cameron, R.E., Hennigar, C.R., MacLean, D.A., Adams, G.W., Erdle, T.A. 2013. A comprehensive greenhouse gas balance for a forest company operating in northeast North America. *Journal of Forestry* 111, 194-205.

Canada. National Roundtable on the Environment and the Economy. 2012. Facing the Elements: Building Business Resilience in a Changing Climate. (Case Studies).

Chiasson, B., Moreau, G. 2021. Assessing the lifeboat effect of retention forestry using flying beetle assemblages. *Forest Ecology and Management* 483, 118784.

Chang, W-Y., Lantz, V.A., MacLean, D.A. 2009. Public attitudes about forest pest outbreaks and control options: case studies in two Canadian provinces. *Forest Ecology and Management* 257, 1333-1343.

Chang, W-Y., Lantz, V.A., MacLean, D.A. 2011. Social benefits of controlling forest insect outbreaks: a contingent valuation analysis in two Canadian provinces. *Canadian Journal of Agricultural Economics* 59, 383-404.

Chang, W-Y., Lantz, V.A., Hennigar, C.R., MacLean, D.A. 2012. Benefit-cost analysis of spruce budworm (Choristoneura fumiferana Clem.) control: incorporating market and non-market values. *Journal of Environmental Management* 93, 104-112.

Colford-Gilks, A.K., MacLean, D.A., Kershaw, J.A., Béland, M. 2012. Growth and mortality of balsam fir- and spruce-tolerant hardwood stands as influenced by stand characteristics and spruce budworm defoliation. *Forest Ecology and Management* 280, 82-92.

D'Astous, É., Villard, M-A. 2012. Effects of selection harvesting on bark invertebrates and nest provisioning rate in an old forest specialist, the brown creeper (Certhia americana). *Ecoscience* 19, 106-112.

Deb, J.C., Forbes, G., MacLean, D.A. 2020. Modelling the spatial distribution of selected North American woodland mammals under future climate scenarios. *Mammal Review* 50, 440-452.

Dracup, E. C., Keppie, D.M., Forbes, G.J. 2015. Woodland mouse and vole response to increased structural diversity following midrotation commercial thinning in spruce plantations. *Canadian Journal of Forest Research* 45, 1121-1131.

Erdozain, M., Kidd, K.A., Negrazis, L., Capell, S.S., Kreutzweiser, D.P., Gray, M.A., Emilson, E.J.S. 2022. Understanding the effects of forest management on streams and rivers: A synthesis of the research conducted in New Brunswick (Canada) 2014-2018. *Forestry Chronicle* 98, 77-88.

Erdozain, M., Emilson, C.E., Kreutzweiser, D.P., Kidd, K.A., Mykytczuk, N., Sibley, P.K. 2020. Forest management influences the effects of streamside wet areas on stream ecosystems. *Ecological Applications* 30, e02077.

Erdozain, M., Kidd, K.A., Emilson, E.J.S., Capell, S.S., Kreutzweiser, D.P., Gray, M.A. 2021a. Elevated allochthony in stream food webs as a result of longitudinal cumulative effects of forest management. *Ecosystems* 1-17.

Erdozain, M., Kidd, K.A., Emilson, E.J.S., Capell, S.S., Kreutzweiser, D.P., Gray, M.A. 2021b. Forest management impacts on stream integrity at varying intensities and spatial scales: Do abiotic effects accumulate spatially? *Science of the Total Environment* 753, 141968.

Erdozain, M., Kidd, K.A., Emilson, E.J.S., Capell, S.S., Luu, T., Kreutzweiser, D.P., Gray, M.A. 2021c. Forest management impacts on stream integrity at varying intensities and spatial scales: Do biological effects accumulate spatially? *Science of the Total Environment* 763, 144043.

Erdozain, M., Kidd, K., Kreutzweiser, D., Sibley, P. 2018. Linking stream ecosystem integrity to catchment and reach conditions in an intensively managed forest landscape. *Ecosphere* 9, 1-29.

Erdozain, M., Kidd, K., Kreutzweiser, D., Sibley, P. 2019. Increased reliance of stream macroinvertebrates on terrestrial food sources linked to forest management intensity. *Ecological Applications* 0, e01889.

Etheridge, D.A., MacLean, D.A., Wagner, R.G., Wilson, J.S. 2005. Changes in landscape composition and stand structure from 1945-2002 on an industrial forest in New Brunswick, Canada. *Canadian Journal of Forest Research* 35, 1965-1977.

Etheridge, D.A., MacLean, D.A., Wagner, R.G., Wilson, J.S. 2006. Effects of intensive forest management on stand and landscape characteristics in northern New Brunswick, Canada (1945-2027). *Landscape Ecology* 21, 509-524.

Fenton, N.J., Frego, K.A. 2005. Bryophyte (moss and liverwort) conservation under remnant canopy in managed forests. B*iological Conservation* 122, 417-430.

Fuller, A.K., Harrison, D.J. 2010. Movement paths reveal scale-dependent habitat decisions by Canada lynx. *Journal of Mammalogy* 91, 1269-1279.

Fuller, A.K., Harrison, D.J., Vashon, J.H. 2007. Winter habitat selection by Canada lynx in Maine: prey abundance or accessibility? *Journal of Wildlife Management* 71, 1980-1986.

Furze, S., Ogilvie, J., Arp, P. 2017a. Fusing digital elevation models to improve hydrological interpretations. *Journal of Geographic Information System* 9, 558-575.

Furze, S., Castonguay, M., Ogilvie, J., Nasr, M., Cormier,P., Gagnon, R., Adams, G., Arp, P. A. 2017b. Assessing soil-related black spruce and white spruce plantation productivity. *Open Journal of Forestry* 7, 209-227.

Furze, S. 2018. A high-resolution digital soil mapping framework for New Brunswick, Canada. PhD Dissertation. University of New Brunswick, Fredericton, New Brunswick, Canada.

Gandiaga, F., Moreau, G. 2016a. How long are thinning-induced resource pulses maintained in plantation forests for beetle species? Unpublished.

Gandiaga, F., Moreau, G. 2016b. Settling in or passing through: deadwood colonization after plantation commercial thinning. Unpublished.

Guénette, J-S., Villard, M-A. 2005. Thresholds in forest bird response to habitat alteration as quantitative targets for conservation. *Conservation Biology* 19, 1168-1180.

Guénette, J-S., Villard, M-A. 2004. Do empirical thresholds truly reflect species tolerance to habitat alteration? E*cological Bulletins* 51, 163-171.

Haché, S., Villard, M-A. 2010. Age-specific response of a migratory bird to an experimental alteration of its habitat. *Journal of Animal Ecology* 79, 897-905.

Haché, S., Cameron, R., Villard, M-A., Bayne, E.M., MacLean, D.A. 2016. Demographic response of a neotropical migrant songbird to forest management and climate change scenarios. *Forest Ecology and Management* 359, 309-320.

Haché, S., Villard, M-A., Bayne, E.M. 2013. Experimental evidence for an ideal free distribution in a breeding population of a territorial songbird. *Ecology* 94, 861-869.

Haughian, S.R., Frego, K.A. 2016. Short-term effects of three commercial thinning treatments on diversity of understory vascular plants in white spruce plantations of northern New Brunswick. *Forest Ecology and Management* 370, 45-55.

Henderson, J., Forbes, G.J. 2010. The effect of pre-commercial thinning on the abundance of small mammals. In: *Forest Dynamics, Succession and Habitat Relationships Under Differing Levels of Silviculture*. Sustainable Forest Management Network, Edmonton, Alberta. 75 pp.

Hennigar, C.R., MacLean, D.A., Porter, K.B., Quiring, D.T. 2007. Optimized harvest planning under alternative foliage protection scenarios to reduce volume losses to spruce budworm. *Canadian Journal of Forest Research* 37, 1755-1769.

Hennigar, C.R., MacLean, D.A., Quiring, D.T., Kershaw, J.A. 2008a. Differences in spruce budworm defoliation among balsam fir and white, red, and black spruce. *Forest Science* 54, 158-166.

Hennigar, C.R., MacLean, D.A., Amos-Binks, L.J. 2008b. A novel approach to optimize management strategies for carbon stored in both forests and wood products. *Forest Ecology and Management* 256, 786-797.

Hennigar, C.R., and Maclean, D.A. 2010. Spruce budworm and management effects on forest and wood product carbon for an intensively managed forest. *Canadian Journal of Forest Research* 40, 1736-1750.

Hennigar, C.R., Erdle, T.A., Gullison, J.J., MacLean, D.A. 2013. Reexamining wood supply in light of future spruce budworm outbreaks: a case study in New Brunswick. *Forestry Chronicle* 89, 42-53.

Higdon, J.W., MacLean, D.A., Hagan, J.M., Reed, J.M. 2005. Evaluating vertebrate species risk on an industrial forest landscape. *Forest Ecology and Management* 204, 279-296.

Higdon, J.W., MacLean, D.A., Hagan, J.M., Reed, J.M. 2006. Risk of extirpation for vertebrate species on an industrial forest in New Brunswick, Canada: 1945, 2002, and 2027. *Canadian Journal of Forest Research* 36, 467-481.

Hoving, C.L., Harrison, D.J., Krohn, W.B., Joseph, R.A., O'Brien, M. 2005. Broad-scale predictions of Canada lynx occurrence in eastern North America. *Journal of Wildlife Management* 69, 739-751.

J.D. Irving, Limited, Forest Supply Chain. 2021. Environment, Social and Governance Report.

J.D. Irving, Limited, Woodlands, 2021. State of the Forest Report.

Jones, M.-F., Castonguay, M., Jaeger, D., Arp, P. 2018. Track-monitoring and analyzing machine clearances during wood forwarding. *Open Journal of Forestry* 8, 297-327.

Keppie, D.M., Haines, J.A., Laurion, I., Theriault, M-C. 2006. Birds and small mammals use intensely managed conifer plantations in northwestern New Brunswick. Unpublished report, 39 pp.

La France, K., Roberts, M.R. 2010. The effect of pre-commercial thinning on the abundance of herbaceous species. In: *Forest dynamics, succession and habitat relationships under differing levels of silviculture*. Sustainable Forest Management Network. Edmonton, Alberta. pp 27-30.

Lemaître, J., Villard, M-A. 2005. Foraging patterns of pileated woodpeckers in a managed Acadian forest: a resource selection function. *Canadian Journal of Forest Research* 35, 2387-2393.

MacKay, A., Allard, M., Villard, M-A. 2014. Capacity of older plantations to host bird assemblages of naturally-regenerated conifer forests: a test at stand and landscape levels. *Biological Conservation* 170, 110-119.

MacLean, D.A., Amirault, P., Amos-Binks, L., Carleton, D., Hennigar, C., Johns, R., Régnière, J. 2019. Positive results of an early intervention strategy to suppress a spruce budworm outbreak after five years of trials. *Forests* 10, 448.

MacLean, D.A., Amos-Binks, L. Adams, G., Pelletier, G., Villard, M-A. 2010a. Legacy of the

Sustainable Forest Management Network: Outcomes of research collaborations among J.D. Irving, Limited, University of New Brunswick, and Université de Moncton. Sustainable Forest Management Network, Edmonton, Alberta, 52 pp.

MacLean, D.A., Adams, G., Pelletier, G., Amos-Binks, L., Carle, J-F., Chicoine, B., Colford-Gilks, A., Forget, P., Haché, S., Henderson, J., La France, K., Poulin, J-F., Smith, M., Ward, C., Witkowski, A., Beckley, T.M., Béland, M., Betts, M.G., Erdle, T.A., Forbes, G.J., Frego, K., Kershaw, J.A., Roberts, M.R., Roy, R., Samson, C., Villard, M-A., Wagner, R.G., Wilson, J.S. 2010b. Forest dynamics, succession and habitat relationships under differing levels of silviculture. Sustainable Forest Management Network. Edmonton, Alberta. 75 pp.

MacLean, D.A., Dracup, E., Gandiaga, F., Haughian, S.R., MacKay, A., Nadeau, P., Omari, K., Adams, G., Frego, K.A., Keppie, D., Moreau, G., Villard, M-A. 2015. Experimental manipulation of habitat structures in intensively managed spruce plantations to increase their value for biodiversity conservation. *The Forestry Chronicle* 91, 161-175.

Monk, W.A., Wilbur, N.M., Curry, R.A., Gagnon, R., Faux, R.N. 2013. Linking landscape variables to cold water refugia in rivers. *Journal of Environmental Management* 118, 170-176.

Montigny, M.K., MacLean, D.A. 2005. Using heterogeneity and representation of ecosite criteria to select forest reserves in an intensively managed industrial forest. *Biological Conservation* 125, 237-248.

Montigny, M.K., MacLean, D.A. 2006. Triad forest management: Scenario analysis of forest zoning effects on timber and non-timber values in New Brunswick, Canada. *The Forestry Chronicle* 82, 496-511.

Moreau, G., Boudreau, D., Chiasson, B., Tousignant, L., Porter, K. 2022. Using LiDAR and machine learning to model forest beetle metacommunity dynamics at the landscape scale. Abstract presented at the North American Forest Ecology Workshop, Turning ecological answers into forest management actions, June 20-24, 2022.

Nadeau, P., Majka, C.G., Moreau, G. 2015a. Short-term response of coleopteran assemblages to thinning-induced differences in dead wood volumes. *Forest Ecology and Management* 336, 44-51.

Nadeau, P., Thibault, M., Horgan, F.G., Michaud, J-P., Gandiaga, F., Comeau, C., Moreau, G. 2015b. Decaying matters: Coleoptera Involved in heterotrophic systems. In: *Beetles: Biodiversity, Ecology and Role in the Environment*. Ed., Camilla Stack. Nova Science Publishers, Inc., New York, pp. 123-174.

Negrazis, L., Kidd, K.A., Erdozain, M., Emilson, E.J.S., Mitchell, C.P.J., Gray, M.A. 2022. Effects of forest management on mercury bioaccumulation and biomagnification along the river continuum. *Environmental Pollution* 310, 119810.

Neilson, E.T., MacLean, D.A., Meng, F.R., Arp, P.A. 2007. Spatial distribution of carbon in natural and managed stands in an industrial forest in New Brunswick, Canada. *Forest Ecology and Management* 253, 148-160.

Neilson, E.T., MacLean, D.A., Meng, F.R., Hennigar, C.R., Arp, P.A. 2008. Optimal on and off site forest carbon sequestration under existing tier supply constraints in northern New Brunswick. *Canadian Journal of Forest Research* 38, 2784-2796.

Olson, S., Harrison, D. 2014. Relationships among forest harvesting, snowshoe hares, and Canada lynx in Maine. Cooperative Forestry Research Unit (CFRU) Annual Report, pp. 68-74.

O'Sullivan, A.M., Devito, K.J., Curry, R.A. 2019. The influence of landscape characteristics on the spatial variability of river temperatures. *Catena* 177, 70-83.

O'Sullivan, A.M., Devito, K.J., D'Orangeville, L., Curry, R.A. 2022. The waterscape continuum concept: Rethinking boundaries in ecosystems. *WIREs Water* 2022, e1598.

O'Sullivan, A.M., Linnansaari, T., Leavitt, J., Samways, K.M., Kurylyk, B.L., Curry, R.A. 2021. The salmon-peloton: Hydraulic habitat shifts of adult Atlantic salmon (Salmo salar) due to behavioural thermoregulation. *River Research and Applications* 38, 107-118.

O'Sullivan, A.M., Wegscheider, B., Helminen, J., Cormier, J.G., Linnansaari, T., Wilson, D.A., Curry, R.A. 2020. Catchment-scale, high-resolution, hydraulic models and habitat maps – a salmonid's perspective. *Journal of Ecohydraulics* 6, 53-68.

Pelletier, G., Pitt, D. 2008. Silvicultural responses of two spruce plantations to midrotation commercial thinning in New Brunswick. *Canadian Journal of Forest Research* 38, 851-867.

Pérot, A., Villard, M-A. 2008. Putting density back into the habitat-quality equation: case study of an open-nesting forest bird. *Conservation Biology* 23, 1550-1557.

Pitt, D., Lanteigne, L. 2008. Long-term outcome of precommercial thinning in northwestern New Brunswick: growth and yield of balsam fir and red spruce. *Canadian Journal of Forest Research* 38, 592-610.

Poulin, J-F., Villard, M-A. 2011. Edge effect and matrix influence on the nest survival of an old forest specialist, the Brown Creeper (Certhia americana). *Landscape Ecology* 26, 911-922.

Poulin, J-F., Villard, M-A., Hache, S. 2010. Short-term demographic response of an old forest specialist to experimental selection harvesting. *Ecoscience* 17, 20-27.

Poulin, J-F., Villard, M-A., Edman, M., Goulet, P.J., Eriksson, A-M. 2008. Thresholds in nesting habitat requirements of an old forest specialist, the Brown Creeper (Certhia americana), as conservation targets. *Biological Conservation* 141, 1129-1137.

Quiring, D., Adams, G., Flaherty, L., McCartney, A., Miller, J.D., Edwards, S. 2019a. Influence of a foliar endophyte and budburst phenology on survival of wild and laboratory-reared eastern spruce budworm, Choristoneura fumiferana on white spruce (Picea glauca). *Forests* 10, 503.

Quiring, D., Flaherty, L., Adams, G., McCartney, A., Miller, J.D., Edwards, S. 2019b. An endophytic fungus interacts with crown level and larval density to reduce the survival of eastern spruce budworm, Choristoneura fumiferana (Lepidoptera: Tortricidae), on white spruce (Picea glauca). *Canadian Journal of Forest Research* 49, 221-227.

Quiring, D., Adams, G., McCartney, A., Edwards, S., Miller, J.D. 2020. A foliar endophyte of white spruce reduces survival of the eastern spruce budworm and tree defoliation. *Forests* 11, 659.

Remus, J., Bennett, J.R., Wilson, S., Adams, G., McIlwrick, K., Mazerolle, M., Smenderovac, E., Venier, L.A. 2023. Modelling the occupancy of two bird species at risk (Canada Warbler and Olive-sided Flycatcher) in a managed Acadian forest landscape: implications for management. Manuscript in preparation.

Research Partnership on Tick-Moose-Climate Interactions. (www.albipictus.com).

Richardson, S.N., Nsiama, T.K., Walker, A.K., McMullin, D.R., Miller, J.D. 2015. Antimicrobial dihydrobenzofurans and xanthenes from a foliar endophyte of Pinus strobus. *Phytochemistry* 117, 436-443.

Rolek, B.W., Harrison, D.J., Loftin, C.S., Wood, P.B. 2018. Regenerating clearcuts combined with postharvest forestry treatments promote habitat for breeding and post-breeding spruce-fir avian assemblages in the Atlantic Northern Forest. *Forest Ecology and Management* 427, 392-413.

Samson, C., Forget, P., Larivière, S., Laurion, I., Pelletier, A-M., Villeneuve, F. 2010. Ecology of American marten (Martes americana) in an industrial forest of northwestern New Brunswick, Canada – Final Report. Faculté de Foresterie, Université de Moncton, campus d'Edmundston, New Brunswick. XIV +66 pages.

Schmalholz, M., Hylander, K., Frego, K. 2011. Bryophyte species richness and composition in young forests regenerated after clear-cut logging versus after wildfire and spruce budworm outbreak. *Biodiversity and Conservation* 20, 2575-2596.

Schortemeyer, C. 2022. Maximizing white spruce (Picea glauca) productivity in a drying climate through tree improvement. Masters thesis, University of New Brunswick, Department of Forestry and Environmental Management.

Simons-Legaard, E.M., Harrison, D.J., Krohn, W.B., Vashon, J.H. 2013. Canada lynx occurrence and forest management in the Acadian Forest. *Journal of Wildlife Management* 77, 567-578.

Simons-Legaard, E.M., Harrison, D.J., Legaard, K.R. 2016. Habitat monitoring and projections for Canada lynx: linking the Landsat archive with carnivore occurrence and prey density. *Journal of Applied Ecology* 53, 1260-1269.

Slaney, G.L., Lantz, V.A., MacLean, D.A. 2009. The economics of carbon sequestration through pest management: application to forested landbases in New Brunswick and Saskatchewan, Canada. *Forest Policy and Economics* 11, 525-534.

Slaney, G.L., Lantz, V.A., MacLean, D.A. 2010. Assessing costs and benefits of pest management on forested landbases in eastern and western Canada. *Journal of Forest Economics* 16, 19-34.

Smith, M., Forbes, G.J., Betts, M.G. 2010. Viability of northern flying squirrel in relation to landscape-scale forest management. In. *Forest Dynamics, Succession and Habitat Relationships Under Differing Levels of Silviculture*. Sustainable Forest Management Network, Edmonton, Alberta. 75 pp.

Spence, C.E., MacLean, D.A. 2011. Comparing growth and mortality of a spruce budworm (Choristoneura fumiferana) inspired harvest versus a spruce budworm outbreak. *Canadian Journal of Forest Research* 41, 2176-2192.

Spence, C.E., MacLean, D.A. 2012. Regeneration and stand development following a spruce budworm outbreak, spruce budworm inspired harvest, and salvage harvest. *Canadian Journal of Forest Research* 42, 1759-1770.

Thériault, S., Villard, M-A., Haché, S. 2012. Habitat selection in site-faithful ovenbirds and recruits in the absence of experimental attraction. *Behavioral Ecology* 23, 1289-1295.

Thibault, M., Moreau, G. 2016a. The amplitude of dead wood resource pulses produced by plantation thinning mediates the assembly of wood-boring beetles. *Ecosphere* 7, e01215.

Thibault, M., Moreau, G. 2016b. Enhancing bark- and wood-boring beetle colonization and survival in vertical deadwood during thinning entries. *Journal of Insect Conservation* 20, 789-796.

Vega-Nieva, D. J. D., Murphy, P. N. C., Castonguay, M., Ogilvie, J., Arp, P. A. 2009. A modular terrain model for daily variations in machine-specific forest soil trafficability. *Canadian Journal of Soil Science* 89, 93-109.

Venier, L.A., Porter, K., Adams, G., McIlwrick, K., Smenderovac, E. 2023. Response of forest bird communities to managed landscapes in the Acadian forest. Manuscript submitted.

Villard, M-A., Haché, S. 2012. Conifer plantations consistently act as barriers to movement in a deciduous forest songbird: a translocation experiment. *Biological Conservation* 155, 33-37.

Villard, M-A., D'Astous, É., Haché, S., Poulin, J-F., Thériault, S. 2012. Do we create ecological traps when trying to emulate natural disturbances? A test on songbirds of the northern hardwood forest. *Canadian Journal of Forest Research* 42, 1213-1219.

Weng, Y.H., Lu, P., Adams, G.W., Fullarton, M.S., Tosh, K.J. 2015. Genetic parameters of growth and stem quality traits for jack pine second-generation progeny tested in New Brunswick. *Canadian Journal of Forest Research* 45, 36-43.

White, T.L., Adams, G.W., Taylor, A.R., Gagnon, R., Sherrill, J.R., McCartney, A.W. 2023. Tree species diversity in managed Acadian forests of eastern Canada. Manuscript submitted.

Wilbur, N.M., O'Sullivan, A.M., MacQuarrie, K.T.B., Linnansaari, T., Curry, R.A. 2020. Characterizing physical habitat preferences and thermal refuge occupancy of brook trout (Salvelinus fontinalis) and Atlantic salmon (Salmo salar) at high river temperatures. *River Research and Applications* 36, 769-783.

Ye, T. 2020. Genetic analysis and gain prediction for white spruce testing programs in New Brunswick. Report, 25 pp.

Ye, T. 2021. Genetic analysis and gain prediction for jack pine testing programs in New Brunswick. Report, 26 pp.

Other literature cited

Chao, A., Gotelli, N. J., Hsieh, E.L., Sander, K.H. Ma, R.K., Colwell, R.K., Ellison, A.M. 2014. Rarefaction and extrapolation with Hill numbers: A framework for sampling and estimation in species diversity studies. *Ecological Monographs* 84: 45-67.

Climate Atlas of Canada (www.climateatlas.ca).

Costanza, K.K.L., Whitney, T.D., McIntire, C.D., Livingston, W.H., Gandhi, K.J.K. 2018. A synthesis of emerging health issues of eastern white pine (Pinus strobus) in eastern North America. *Forest Ecology and Management* 423, 3-17.

Duflot, R., Fahrig, L., Mönkkönen, M. 2022. Management diversity begets biodiversity in production forests landscapes. *Biological Conservation* 268, 109514.

Erdle, T., Pollard, J. 2002. Are plantations changing the tree species composition of New Brunswick's forest? *The Forestry Chronicle* 78, 812-821.

Fenton, N.J., Frego, K.A., Sims, M.R. 2003. Changes in forest bryophyte (moss and liverwort) communities 4 years after forest harvest. *Canadian Journal of Botany* 81, 714-731.

Gray, D.R., MacKinnon, W.E. 2006. Outbreak patterns of the spruce budworm and their impacts in Canada. *The Forestry Chronicle* 82, 550-561.

Greenbank, D.O. 1970. Climate and the ecology of the Balsam wooly aphid. *Canadian Entomologist* 102, 546-578.

Hill, M. 1973. Diversity and evenness: A unifying notation and its consequences. *Ecology* 54: 427-32.

Hushaw, J., Walberg, E., Balch, S. 2018. Climate Change and Forestry Handbook. Climate Smart Land Network, Manomet, Plymouth, MA.

Langevin, R., Plamondon, A.P. 2004. Méthode de cacul de l'aire équivalente de coupe d'un basin versant en relation avec le débit de point des cours d'eau dans la forêt à dominance résineuse, gouvernement du Québec, ministère des Ressources naturelles, de la Faune et des Parcs, Direction de l'environnement forestier et Université Laval, Faculté de foresterie et de géomatique, code de diffusion, 24 p.

Livingston, W.H., Munck, I., Lombard, K., Weimer, J., Bergdahl, A. 2019. MP764: Field manual for managing eastern white pine health in New England. Maine Agricultural and Forest Experiment Station Miscellaneous Publications, 20 pp.

Loo, J., Cwynar, L., Freedman, B., and N Ives. 2010. Changing forest landscapes in the Atlantic Maritime Ecozone. In: *Assessment of Species Diversity in the Atlantic Maritime Ecozone*. McAlpine, Z.D.F., Smith, I.M. (eds). NRC Research Press, Ottawa, Canada. pp. 35-42.

Miller, J.D. 2011. Foliar endophytes of spruce species found in the Acadian forest: basis and potential for improving the tolerance of the forest to spruce budworm. In: *Endophytes of forest trees: biology and applications*. Frank, C.A., Pirttila, A.M. (eds). Springer, New York. pp. 237-249.

Moore, I.D., Gessler, P.E., Nielsen, G.A., Peterson, G.A. 1993. Soil attribute prediction using terrain analysis. *Soil Science Society of American Journal* 57, 443–452.

Moreau, G., Chagnon, C., Achim, A., Caspersen, J., D'Orangeville, L., Sánchez-Pinillos, M., Thiffault, N. 2022. Opportunities and limitations of thinning to increase resistance and resilience of trees and forests to global change. *Forestry* 95, 595-615.

Murphy, P.N.C., Ogilvie, J., Connor, K., Arp, P.A. 2007. Mapping wetlands: A comparison of two different approaches for New Brunswick, Canada. *Wetlands* 27, 846–854.

Murphy, P.N.C., Ogilvie, J., Meng, F., Arp, P.A. 2008. Stream network modelling using Lidar and photogrammetric digital elevation models: a comparison and field verification. *Hydrological Processes* 22, 1747–1754.

National Research Council. 1995. Wetlands: Characteristics and Boundaries. Washington, DC: The National Academies Press.

North American Bird Conservation Initiative. 2022. The State of the Birds, United States of America. 17 pp.

Odgers, N.P., Sun, W., McBratney, A.B., Minasny, B., Clifford, D. 2014. Disaggregating and harmonising soil map units through resampled classification trees. *Geoderma* 214, 91–100.

Ohlmann, M., Miele, V., Dray, S., Chalmandrier, L., O'Connor, L., Thuiller, W. 2019. Diversity indices for ecological networks: a unifying framework using Hill numbers. *Ecology Letters* 22: 737-747.

Old Forest Communities and Old-forest Wildlife Habitats in New Brunswick. 2017. New Brunswick Department of Energy and Resource Development, 22 pp.

Old-forest Thresholds for New Brunswick's Crown Forest. 2017. New Brunswick Department of Energy and Resource Development, 10 pp.

Pitty, A.F. 1979. Geography and Soil Properties. Methuen, London.

Potter, K.M., Crane, B.S., Hargrove, W.W. 2017. A United States national prioritization framework for tree species vulnerability to climate change. *New Forests* 48, 275-300.

Seymour, R.S., Hunter, M.L. 1992. New Forestry in Eastern Spruce-Fir Forests: Principles and Applications to Maine. Orono, ME: University of Maine.

Ste-Marie, C., Nelson, E.A., Dabros, A., Bonneau, M-E. 2011. Assisted migration: Introduction to a multifaceted concept. *The Forestry Chronicle* 87, 724-730.

Tanney JB, McMullin DR, Miller JD (2018) Toxigenic foliar endophytes from the Acadian Forest. In: *Endophytes of forest trees: biology and applications*. Frank, C.A., Pirttila, A.M. (eds). Springer, New York. pp. 343-381.

Taylor, A.R., Boulanger, Y., Price, D.T., Cyr, D., McGarrigle, E., Rammer, W., Kershaw, J.A. 2017. Rapid 21st century climate change projected to shift composition and growth of Canada's Acadian Forest Region. *Forest Ecology and Management* 405, 284-294.

The State of Canada's Birds. 2019. nabci Canada. 12 pp.

Vaughn, W.R., Taylor, A.R., MacLean, D.A., D'Orangeville, L., Lavigne, M.B. 2021. Climate change experiment suggests divergent responses of tree seedlings in eastern North American's Acadian Forest Region over the 21st century. *Canadian Journal of Forest Research* 51, 1888-1902.

Ward, C., Erdle, T. 2015. Evaluation of forest management strategies based on Triad zoning. *The Forestry Chronicle* 91, 40-51.

Zelazny, V.F. (Ed.). 2007. Our Landscape Heritage: The Story of Ecological Land Classification in New Brunswick (2nd ed). New Brunswick Dept. Natural Resources, Fredericton, New Brunswick. 359 pp.

Zhu, A.-X., Mackay, S.D. 2001. Effects of spatial detail of soil information on watershed modeling. *Journal of Hydrology* 248, 54–77.

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