Adaptive silviculture for climate change in the Great Lakes-St. Lawrence Forest Region of Canada: Background and design of a long-term experiment

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ABSTRACT

We present the implementation of the Adaptive Silviculture for Climate Change (ASCC) initiative at the Petawawa Research Forest (PRF) in Ontario, Canada. The study addresses the urgent need for adaptive forest management strategies in response to climate change by examining silvicultural treatments aimed at mitigating its impacts on forest ecosystems. It addresses the complex interplay between climate change projections, regional climate characteristics, and forest management practices for pine dominated forests in the Great Lakes-St. Lawrence Forest region of Canada, underscoring the importance of adaptive approaches in sustaining forest ecosystems. We outline the design and objectives of five distinct treatments—control, business-as-usual, resistance, resilience, and transition—implemented over 4 replicate blocks on a 212-ha area at the PRF. We provide detailed descriptions of each treatment's management objectives, desired future conditions, and silvicultural strategies. We conclude by summarizing planned research efforts, including seedling survival assessments, phenological monitoring, and measuring treatment impact on fuel loads. By addressing the challenges and opportunities of climate change as part of an international research network, this research will contribute to a deeper understanding of forest ecosystem responses to climate change and inform adaptive management strategies for sustainable forest management.

Keywords: silvicultural research, adaptive forest management, field experiment, methods, assisted migration, shelterwood harvest, forest regeneration

RÉSUMÉ

Nous présentons la mise en œuvre de l'initiative de sylviculture d'adaptation aux changements climatiques (ASCC) à la forêt de recherche de Petawawa (PRF) en Ontario, Canada. L'étude répond au besoin urgent de stratégies d'aménagement adaptatives en réponse aux changements climatiques en examinant les traitements sylvicoles visant à atténuer ses impacts sur les écosystèmes forestiers. Elle aborde l'interaction complexe entre les projections de changements climatiques, les caractéristiques climatiques régionales et les pratiques sylvicoles pour les forêts dominées par le pin dans la région forestière des Grands Lacs et du Saint-Laurent au Canada, soulignant l'importance des approches adaptatives dans le maintien des écosystèmes forestiers. Nous décrivons la conception et les objectifs de cinq traitements distincts – témoin, cours normal des affaires, résistance, résilience et transition – mis en œuvre sur quatre blocs répliqués dans une zone de 212 ha de la PRF. Nous fournissons des descriptions détaillées des objectifs d'aménagement de chaque traitement, des conditions futures souhaitées et des stratégies sylvicoles. Nous concluons en résumant les efforts de recherche prévus, y compris les évaluations de la survie des semis, le suivi phénologique et l'évaluation de l'effet des traitements sur les combustibles. En s'intéressant aux défis et aux opportunités associés aux changements climatiques dans le cadre d'un réseau de recherche international, ce projet contribuera à une meilleure compréhension des réponses des écosystèmes forestiers aux changements climatiques et supporte le développement de stratégies d'adaptation pour une gestion durable des forêts.

Mots-clés: recherche en sylviculture, gestion adaptative des forêts, expériences terrain, méthodes, migration assistée, coupe progressive, régénération forestière

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Introduction

Persistent greenhouse gas emissions result in a progressive rise in global temperatures, with the most recent projections indicating a potential increase of 1.5 °C in the foreseeable future (IPCC 2023). This rapid change will lead to ecological disruptions and altered functionality of forest ecosystems (Allen *et al.* 2010; Pecl *et al.* 2017; Trisos *et al.* 2020). While there are uncertainties in climate change predictions, some impacts are already being observed and could become more pronounced in the coming decades. For example, there is an observed increase in the frequency of regeneration failures, notably due to high temperatures and water deficits (Boucher *et al.* 2020), which will have repercussions on species composition, forest cover and the sustainable implementation of forest management activities in general (Coop *et al.* 2020; Cyr *et al.* 2022; Stevens-Rumann *et al.* 2022). It is expected that climate shifts will be faster than the natural migration rates of many tree species (Ash *et al.* 2017). These transformations may result in a loss of forest cover and forest ecosystem services, including carbon sequestration, habitat provision, and wood fibre.

In addition to the expected changes from increased temperatures, climate change introduces substantial yet elusive unknowns that require adaptive silviculture activities (Achim *et al.* 2022). In response to these challenges and uncertainties, innovative research has been conducted on the development of silvicultural approaches to reduce risk and mitigate impacts. This includes assisted migration of seed and seedlings (e.g., Palik *et al.* 2022; Royo *et al.* 2023), various thinning regimes (e.g., Moreau *et al.* 2022; Rubio-Cuadrado *et al.* 2024), or regeneration methods (e.g., Hébert *et al.* 2024). Results from such research is leading to the implementation of new silvicultural practices and management strategies to address future uncertainties (Puettmann 2011; Royer-Tardif *et al.* 2021), with the overarching goal to adapt forest ecosystems to novel dynamics, including changes in disturbance and climate regimes (D'Amato *et al.* 2023).

In this paper, we present a research effort in adaptive silviculture for climate change conducted within the Great Lakes-St. Lawrence Forest region of Canada, in which we test adaptation options for pine-dominated forests in a context of an anticipated increase in temperature and drought stress. We describe the conceptual framework which inspired and supported the design of this silviculture experiment, as well as its integration within a larger network of field experiments across northern North America. We provide a brief overview of the forest's ecological and climatic context in which the experiment is located. We then elaborate on the experimental design that was implemented to compare resistance, resilience, and transition treatments with a business-as-usual control and unharvested control conditions. We summarize some of our short-term and long-term research questions and data acquisition plans. Finally, we identify potential opportunities for future research. Overall, our goal is to offer comprehensive background information about this significant research installation. We anticipate that the detailed description of the experiment will stimulate collaborative efforts and technical transfer initiatives.

The ASCC network

The Adaptive Silviculture for Climate Change initiative (ASCC) is a large experimental project aimed at collaboratively developing silvicultural strategies to manage the adverse impacts of future climate conditions on the provision of goods and services from managed forests (Nagel *et al.* 2017). The network includes sites across the United States of America and Canada. At each location, stakeholders, land managers, and research scientists collaborate in a workshop to identify silviculture treatments that are locally applicable, following four climate adaptation strategies based on the concepts described by Millar *et al.* (2007):

1. inaction – allowing forest stands to react to climate change without any direct management;
2. resistance – maintaining forest stand conditions relatively unchanged over time by improving the defenses of the forest to climate change;
3. resilience – managing the forest to accommodate change and rebound from disturbances. Some changes to forest condition are expected but the forest should continue to function similarly to the original; and
4. transition – proactively promoting change in forest stands to stimulate adaptive responses to expected future conditions. This forest will likely look different from the original but still provide similar ecosystem products and services.

For the resistance, resilience and transition treatments, participants define the desired future conditions, identify forest management objectives that align with those conditions, and propose silvicultural prescriptions to achieve the objectives of each adaptation approach (e.g. Crotteau *et al.* 2019). Individual research teams are responsible for establishing and managing sites in the ASCC network. Each team implements the treatments, and monitors regeneration success and stand conditions over time (e.g. Muller *et al.* 2019, 2021), following basic protocols that ensure the compatibility of research data across locations. In time, the network approach of a common research framework and experimental design will enable tackling a range of overarching research questions, including the applicability of adaptation approaches and treatments in meeting local management goals and objectives.

The Petawawa Research Forest (PRF)

Site characteristics

The Petawawa Research Forest (PRF) is located near Chalk River, Ontario, Canada, within the Great Lakes-St. Lawrence Forest Region. The PRF is a federally-owned property established in 1918 and managed by Natural Resources Canada. The forest covers approximately 10 000 ha, with a forest cover comprised predominantly of white pine (*Pinus strobus* L.), with presence of red pine (*Pinus resinosa* Ait.), trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.) and red oak (*Quercus rubra* L.). Soils are mostly dystric brunisol (Soil Classification Working Group 1998) characterized by an acidic, mor-type humus layer, underlain by alluvial medium sands. Natural disturbance regimes include sporadic windthrow events and insect infestations by species such as *Lymantria dispar* L. and *Choristoneura fumiferana* Clem., as well as forest fire prior to European settlement and fire suppression activities.

Past and predicted regional climate

The study region is characterized by a continental climate with an average annual temperature of 5.1 °C and receives 874 mm of precipitation annually (Environment Canada 2010). The mean length of the growing season is 136 days, with January and July, respectively, being the coldest and warmest months.

Anticipated impacts of climate change for the PRF include more frequent snow and ice storms, warmer winters with increased evapotranspiration, and greater summer moisture stress due to potential drought conditions. Projections from Wotherspoon *et al.* (2022, 2024) consolidate the mean changes across all Shared Socioeconomic Pathways (SSP) scenarios of 13 General Circulation Models, providing a comprehensive outlook for the PRF's climatic trajectory[1]. Projections suggest a precipitation increase over the next century. By 2050, under the SSP5-8.5 (rapid development) scenario, the PRF will go through an anticipated increase of 6% precipitation by 2050 and 13% by 2090 with a total of 984 mm annually. Of this, winter precipitation is expected to increase by 17% by 2050 and 34% by 2090. Because the mean minimum winter temperatures are projected to increase by 9.3 °C by 2090 (for an average of -5.7 °C by 2100), precipitation falling as snow is expected to decrease by 28% and 69% by 2050 and 2090, respectively. Summer precipitation is forecasted to be reduced by 3% by 2050 and by 5% by 2090, averaging 248 mm by 2090. Maximum summer temperatures are projected to increase by 3.0 °C and 6.7 °C by 2050 and 2090, respectively, for a mean maximum summer temperature of 31.9 °C by 2090. Mean annual minimum and maximum temperatures are expected to increase to 6.6 °C and 17.5 °C by 2090, respectively. Climate moisture index (CMI) is expected to decrease annually by 8.5 mm by 2050 and by 22.7 mm by 2090 for an annual CMI mean of 9.3 mm (Fig. 1). Increasing annual precipitation allows for an overall positive annual CMI through the end of the century indicating sufficient moisture to sustain a closed-canopy forest, despite rising annual temperatures (Hogg 1994, 1997). However, during future summer months, CMI is expected to decrease from its historical value of -5.8 mm to -10.6 and -18.7 mm by 2050 and 2090, respectively, at which point conditions become too dry to support a closed-canopy forest and will likely shift towards a discontinuous forest (Hogg 1994, 1997).

Implementing ASCC at the PRF

Collaborative Workshop

The collaborative workshop for the PRF site was held July 16–18, 2019, in Pembroke, Ontario to engage local managers, researchers, and stakeholders in a facilitated discussion to develop the ASCC study site's silvicultural treatments at the PRF. The first day was an information session that was attended by 37 individuals from academia, industry and government researchers. A smaller group of 21 researchers, academia, and local forest managers drafted the treatment plan over the next two days. An overview of the workshop is provided by Prevost (2020).

Stand selection and experimental design

In 2019–2020, we identified four harvest blocks within the PRF, totaling approximately 212 ha, which defined the four replicates of the experiment. Each block included enough contiguous stand area for the allocation of one full replicate of the treatments (Fig. 2). Blocks reflect geographical locations rather than underlying site or stand conditions. Our focus was on selecting mature (≥ 80 years), white pine-dominated (≥ 30% white pine + red pine, with white pine > red pine) stands, deemed accessible and suitable for management under the uniform shelterwood system. With few exceptions, stands needed to have at least 60% crown closure and a minimum merchantable basal area (BA) of 15 m^2/ha. Species composition at the PRF is spatially heterogenous, often driven by bedrock constrained topographic variability and resultant changes in soil moisture and nutrient availability. Additional variation is the result of past small scale forest management activities. To ensure contiguous treatment units, alternate stand types were incorporated into the research area. These stands were typically small areas dominated by red oak where white pine accounted for at least 20% of the basal area. Eligible stands were selected based on the attributes contained in the enhanced forest inventory for the PRF (White *et al.* 2021a) and through subsequent ground validation. Areas that were expected to be inoperable due to steep slopes (>20% slope) were excluded. The raster of slope percentage (25 m resolution) was aggregated from a higher resolution raster of slope generated by SAGA (Conrad *et al.* 2015) from the LiDAR-derived digital elevation model (White *et al.* 2021b).

Each block was divided into five experimental units, each covering an average of 10.6 ha (range 8.0–20.5 ha; Fig. 2). Within each experimental unit, raster cells were stratified based on both the topographic wetness index (generated by SAGA from the digital elevation model) and the merchantable basal area (White *et al.* 2021a), and 16.1 m-radius circular plots were randomly located within each of the experimental units, with plot centre locations being no closer than 50 m apart and no closer than 50 m from a boundary or road (Fig. 2). We then calculated the average pixel values for topographic wetness index (TWI) and BA within the plots and used those values to stratify plots into nine classes, representing three levels of each, from low to high (Fig. 2). Within each experimental unit we randomly selected plots from each of the nine classes until either seven or 14 plots, depending on treatment applied (see below), were assigned. By stratifying plots this way, we ensured to have a reasonably comprehensive coverage of plots across the observed spectrum of site and stand conditions found in the blocks (Fig. 2).

Treatments and associated management goals

In each block, we randomly assigned one of five treatments to each of the five experimental units:

1. a control treatment, in which no harvesting occurs;
2. a business-as-usual treatment;
3. a resistance treatment;
4. a resilience treatment; and
5. a transition treatment.

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[1] See Supplementary material Table S1. Mean historical data and future projections for the Petawawa Research Forest in Chalk River, Ontario under four shared socioeconomic pathway (SSP) scenarios.

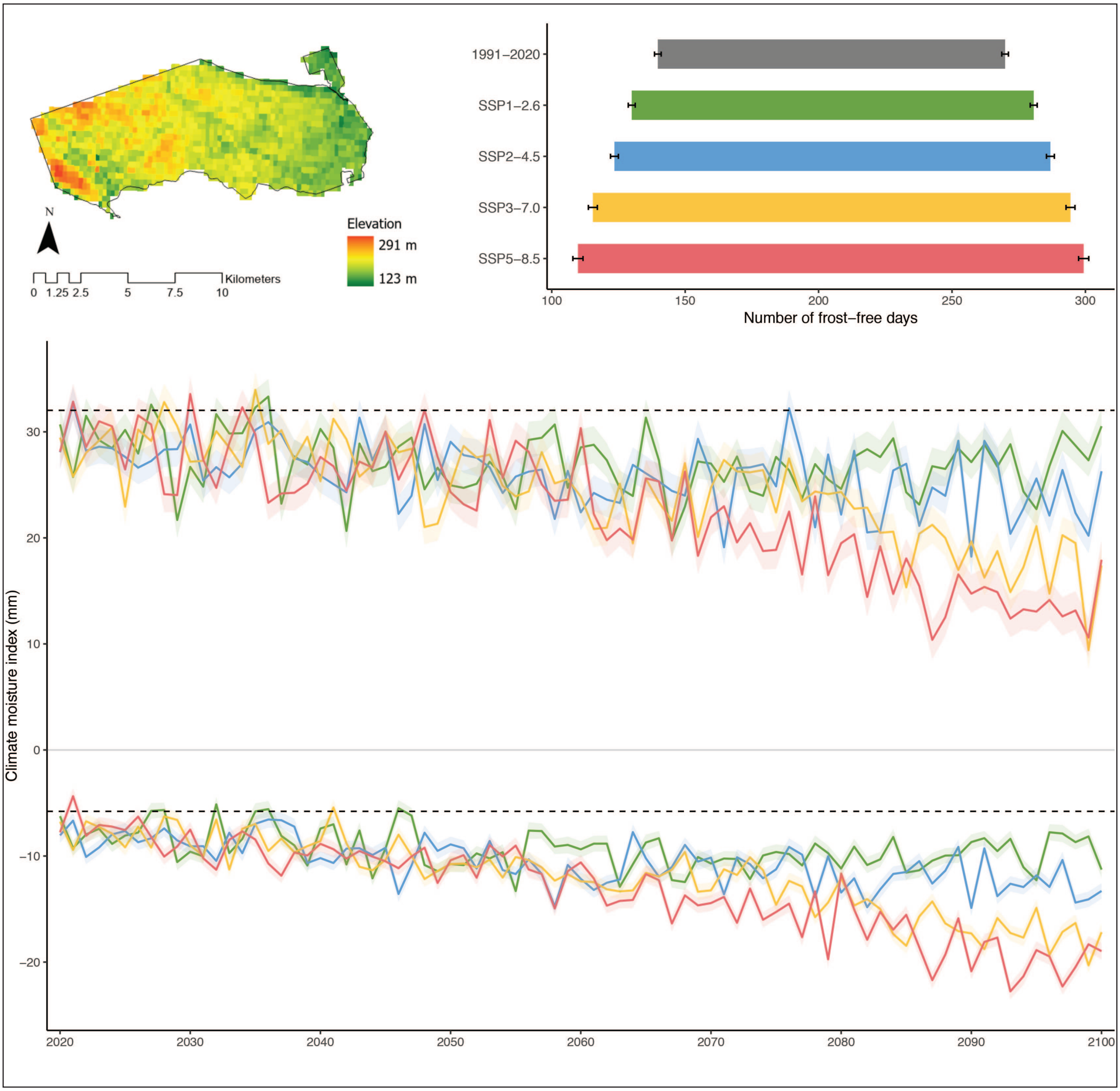

Fig. 1 Climate projections for the Petawawa Research Forest in Chalk River, Ontario, Canada, (top left) for four shared socioeconomic pathway (SSP) scenarios generated using a 13-general circulation model (GCM) ensemble relative to the 1991–2020 period. Colours for each SSP scenario shown for the mean number of frost-free days (top right) correlate to the lines for projected climate moisture index (CMI; mm) (bottom). The CMI lines on the top show projected mean annual values, whereas the bottom CMI lines are projections for mean summer (June, July, August) values. Horizontal black dashed lines represent means for the 1991–2020 reference period.

For each treatment, we identified a set of management objectives, desired future conditions, and silvicultural strategies for each option. The treatments encompassed a gradient of strategies aimed at either maintaining the current forest composition and condition or actively managing for change to create a new forest condition that is better suited to cope with the challenges posed by climate change in the PRF region.

Control treatment

In the control treatment, we selected mature stands representing the desired future condition throughout the study's duration. Control stands will be monitored and serve as a benchmark for natural succession in the absence of management.

Business-as-usual control treatment

The business-as-usual scenario involved implementing a two-cut uniform shelterwood system. It represents the standard management approach for white pine dominated stands in the region. Its aim was to regenerate a well-stocked, productive stand dominated by pine species, such as white pine and other drought-tolerant species commonly found in the area. This system serves the dual purpose of ensuring a viable seed

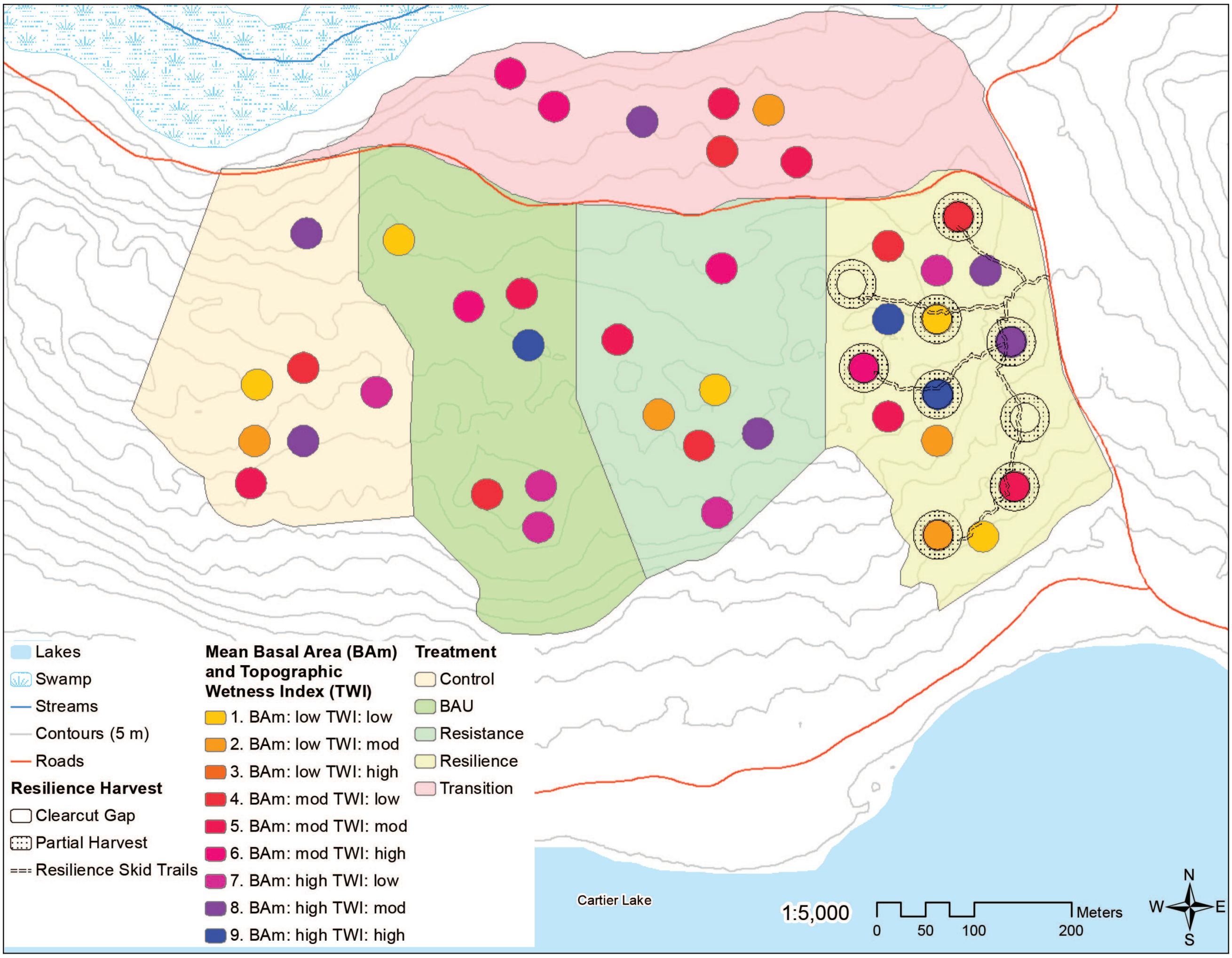

Fig. 2 Example of one replicate block from the ASCC experiment at the Petawawa Research Forest in Chalk River, Ontario, Canada. Circles represent 16.1 m-radius circular plots stratified based on mean basal area and topographic wetness index. BAU: business-as-usual.

source and modulating light level in the understory (Nyland *et al.* 2016). Additionally, it maintains or increases the production of high-quality sawlogs and other forest products, while managing for wildlife habitat and pest mitigation. The seed cut targeted a residual basal area of 12–14 m^2/ha. The final cut will be performed when the height of white pine regeneration reaches 6 m, a height at which risks of white pine weevil (*Pissodes strobe* Peck) damages are significantly reduced (Ostry *et al.* 2010; OMNRF 2019). At this stage, regeneration should be comprised of a minimum of 600 stems/ha of desirable species. The first stage of this treatment was implemented with a harvesting treatment in 2021, followed by mechanical site preparation with a rake, and chemical site preparation with glyphosate (VisionMax Silviculture Herbicide, Monsanto Canada, Winnipeg, MB; 1.5% v:v in water) in the fall of 2023. Natural regeneration of white pine, red pine, red oak, and spruce (*Picea* spp.) will be encouraged, along with the planting of white pine and red pine from local sources (see below). Necessary tending will be carried out during the initial 40 years to ensure species composition targets are met. The final rotation is expected to occur within 80–100 years. The planting strategy for this treatment was to populate the site with locally adapted white and red pine (see below).

Resistance treatment

The resistance treatment aimed to achieve similar management objectives to the business-as-usual treatment, using a two-cut shelterwood system. The goal was to achieve a future condition of a white pine-dominated forest, but with an emphasis on expanding the genetic diversity of white pine to include several different climate zone and future climate adapted seed sources (see below). These alternate seed sources are expected to improve the ability of the stands to tolerate future climate conditions. The initial harvest occurred in the fall and winter of 2021 and was followed by mechanical and chemical site preparation in summer and fall of 2023, respectively.

Resilience treatment

The resilience treatment sought to achieve a structurally diverse white pine and red oak dominated forest, while prioritizing resilience to disturbances by adding structural diversity across the treatment area as well as by adding additional species and seed source diversity within the harvested areas. We implemented a modified version of the irregular shelterwood system with expanding gaps (Raymond *et al.* 2009; Raymond and Bédard 2017). The management goals for this treatment consists of promoting a well-stocked, multi-aged stand, maintaining or increasing productivity and quality of wood products, increasing resilience to disturbances, enhancing species diversity, and establishing trees adapted to future climate conditions. We created clearcut gaps, each with a radius of 15 m, and an additional 10 m perimeter edge, where 50% of the overstory and all the understory was removed around each gap. At the stand level, this silviculture treatment establishes a mosaic pattern of uncut, mature forests, with harvested areas covering 20–25% of the stand area.

Chemical site preparation was carried out for understory vegetation management in the fall of 2023, primarily with backpack sprayers. The harvested areas were regenerated using white pine, red oak and white oak (*Quercus alba* L.) sourced from climate-adapted locations (see below). The natural regeneration of white pine and red oak will also be promoted. Gap expansion is planned to occur by increments of 20–25% of the stand area, every 15–20 years. This provides an opportunity for a relatively quick adaptive forest management strategy and provides the opportunity to evaluate and adjust planted species and seed zones to accommodate changing climatic conditions and new knowledge.

Transition treatment

The transition treatment involved actively facilitating change to create a climate-adapted forest that should maintain essential ecosystem functions (e.g., water filtration, carbon sequestration) and services over the next rotation. We used a clearcut with seed trees harvest (Nyland *et al.* 2016; OMNRF 2019), retaining 16–35 stems/ha of dispersed large white and red pine to preserve structure and provide seed source for natural regeneration. By moving away from the typical shelterwood silviculture system, increasing genetic diversity of local species, and replacing the primary species with novel species (pitch pine, *Pinus rigida* Mill.), we hope to achieve a future forest that is better suited to warmer and drier conditions. Our management goals for this treatment focused on providing quality wood products, promoting a diverse species mix adapted to climate-related challenges, and ensuring wildlife habitat through structural retention and an increase in mast producing species. Similar to the other treatments, the mechanical site preparation was conducted in summer 2023 and chemical site preparation was completed in fall 2023, following the 2021 harvest. Ongoing tending will be conducted as necessary after the establishment of pitch pine, red pine, red oak and white oak of various climate-adapted seed sources (see below).

Pre-harvest measurements

During the fall of 2020 and summer of 2021, we established and assessed the measurement plots. Plots were circular with a radius of 16.1 m, to which we superimposed sub-plots of varying surface areas for the measurement of live trees, saplings, regeneration, seedlings, standing dead trees, downed coarse woody debris, and ground vegetation (Fig. 3). Also, we collected data on surface substrates (assessed within the ground layer plots), and soil composition (carbon and nutrient content).

Seed procurement, seedling production and planting/sowing

We used the SeedWhere software (McKenney *et al.* 1999) to map climate similarities between geographic regions and the projected climates based on the Representative Concentration Pathway (RCP) 8.5 at the PRF over the time horizons of 2011–2040, 2041–2070, and 2071–2100 (Fig. 4). SeedWhere is a web application that serves as a climate similarity mapping tool, facilitating the matching of seed sources with planting sites in both current and future climates. It offers a systematic approach to pinpoint potential seed zones, aiding in informed decision-making for sustainable planting practices. Using the Gower metric, we identified seed sources for various species that closely matched the anticipated climates. We then acquired seeds from diverse regions from Ontario, Wisconsin, Iowa, and Virginia (Table 1), while considering seed availability, germination rate, and quality. Pines and red oak seedlings were produced from the seeds during spring and summer 2023 at the Ferguson Tree Nursery in Kemptville, Ontario, in Jiffy 36 mm or Jiffy 50 mm containers (Jiffy Group, Lorain, OH), depending on species.

The white pine, red pine, pitch pine, white and red oaks were planted between in August and September 2023.White oak acorns were directly sown in the resilience measurement plots, as logistical constraints prevented their availability as seedlings. Seedlings/acorns of different species and genotypes were planted/sown at densities ranging from 128 to 1138 seedling/ha, according to the prescribed climate period and treatment (see Table 1). Overall planting/sowing densities, within the experimental units, ranged from 1260 to 1783 seedlings/ha. To enable long-term assessment of survival and growth, we tagged each seedling and acorn sowing location in measurement plots with a pigtail and assigned a uniquely numbered tag. Tagged seedlings will be assessed for their survival, height and general conditions periodically throughout the duration of the study.

Opportunities for future research and conclusions

The ASCC installation at the PRF includes over 173 000 planted seedlings or sowed acorns, with approximately 17 000 individually tagged for measurement within plots. These seedlings represent 11 distinct combinations of species and genotypes, distributed across 16 experimental units (excluding unplanted control plots), which average more than 10 hectares each. This large, operational-scale experimental design presents multiple opportunities for short-, mid-, and long-term research, including both fundamental and applied aspects.

In addition to monitoring the survival and growth of planted seedlings to evaluate the adaptive silviculture strategies in terms of achieving management objectives, we are assessing various other forest attributes. These include overstory tree health and volume, species diversity, abundance of different size classes of advanced regeneration, understory plant composition and functional diversity, abundance and composition of coarse and fine woody debris, and soil nutrient availability. Within a subset of plots, we are monitoring soil temperature and moisture at different depths, air temperature, relative humidity, and photosynthetically active radiation. In addition, we are monitoring snow depth, length of the snow-free season, growing season duration, and leaf

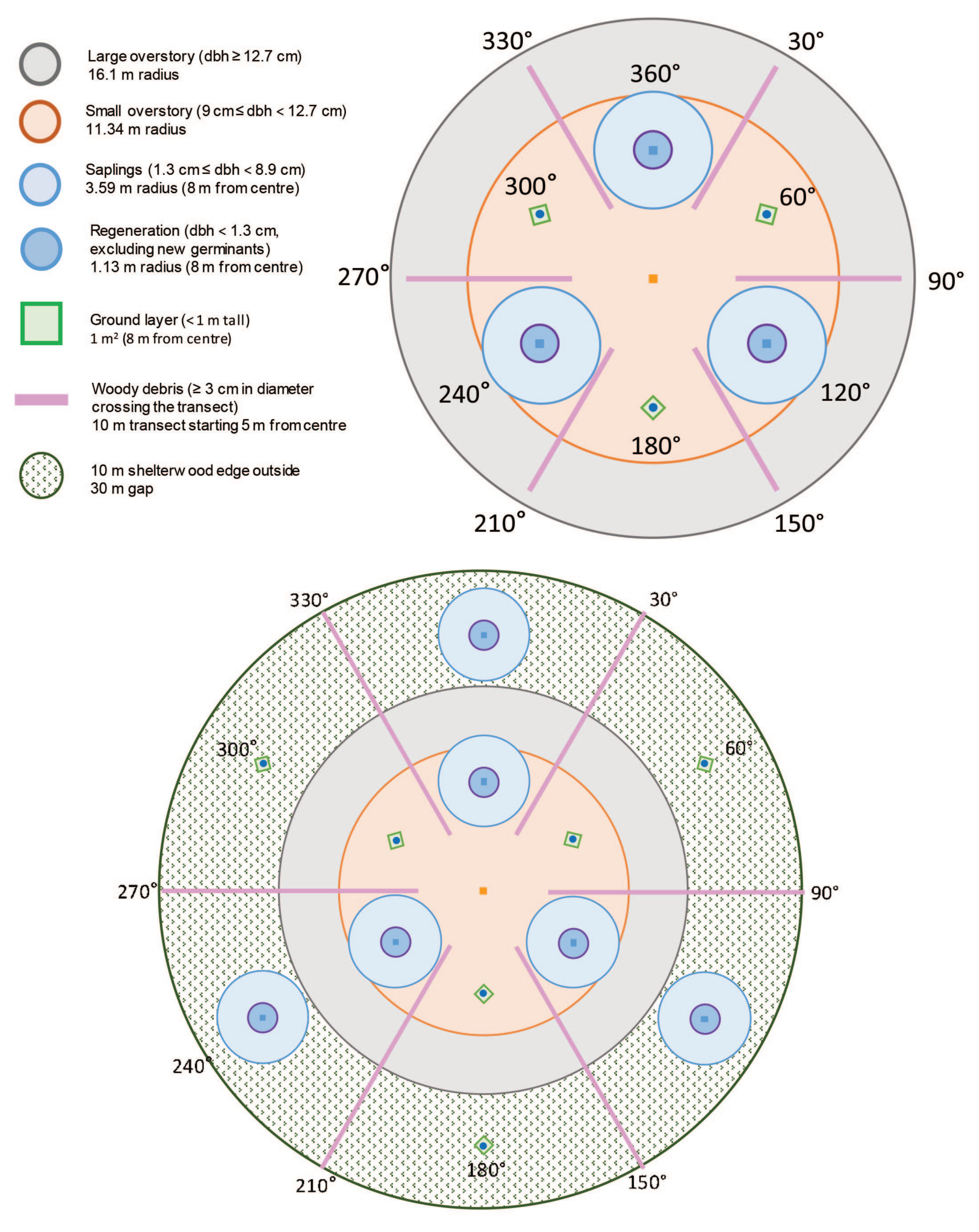

Fig. 3 Schematic representation of the measurement plots in the ASCC experiment at the Petawawa Research Forest in Chalk River, Ontario, Canada, showing the various types of sup-plots. Measurement plots illustrated at the bottom were established in the resilience treatment only; all other treatments are measured using plots as shown in the top right corner. dbh: diameter at breast height (1.3 m).

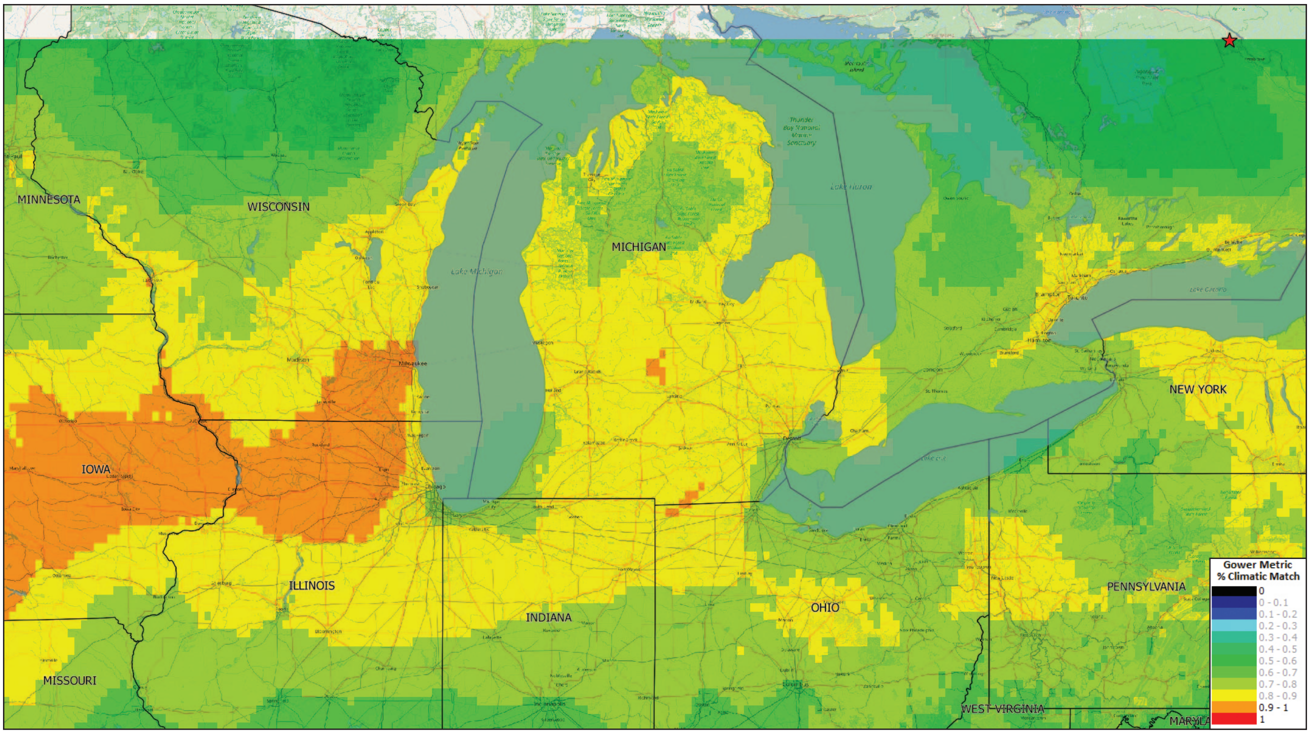

Fig. 4 Example of a map generated by SeedWhere (McKenney *et al.* 1999) used to delineate suitable seed sources in Iowa, USA, for cultivating red oak seedlings, tailored to meet the management goals of the transition treatment, climate period 2041–2070, within the ASCC experiment conducted at the Petawawa Research Forest in Chalk River, Ontario, Canada (see Table 1). The red star at the top right of the map shows the location of the Petawawa Research Forest.

onset and offset dates for various species and seed sources using phenocams (Sonnentag *et al.* 2012). Bird observations have been conducted in a subset of plots, during the breeding seasons, using autonomous recording units (Pérez-Granados and Traba 2021). Similarly, we use camera traps to monitor wildlife in the same subset of plots (Burton *et al.* 2015). Future work will also involve quantifying CO_2 pools and fluxes influenced by the various treatments, as well as modeling carbon and growth under various climate change scenarios.

Given the predicted increase in fire risks in Canadian forests due to climate change (Wang *et al.* 2017) and the need to develop “fire-smart” silviculture, we also aim to evaluate the effectiveness of the adaptive silviculture treatments in mitigating fire risk and reducing fuel loads. This will involve investigating the impact of stand density, forest type, forest structure, and soil moisture on fire risk and fuel loads, as well as examining the influence of plant species composition on fire resilience and drought resistance.

In conclusion, the implementation of the ASCC initiative at the Petawawa Research Forest represents an important step towards addressing the complexities of climate change in forest management. By integrating adaptive silvicultural treatments and comprehensive research efforts at an operational scale, as part of an international network of experiments based on the same conceptual framework, this study will enhance our understanding of forest ecosystem responses to climate change. It will also provide valuable insights into effective adaptive management strategies. As we navigate the uncertainties of the future climate, our findings will support informed decision-making and sustainable forest management practices in Canada and elsewhere. Our hope is that this experiment will serve as a significant platform for collaborative research, the training of highly qualified personnel, as well as technology development and transfer for decades to come.

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Table 1. Species planted in 2023 (and seed sources) in the business-as-usual and adaptive silviculture treatments of the ASCC experiment conducted at the Petawawa Research Forest in Chalk River, Ontario, Canada, with the corresponding assisted migration strategy.

	Treatments									
	Resistance	**Resilience**			**Transition**				**Business-as-Usual**	
Silviculture System	Uniform shelterwood	Expanding gap irregular shelterwood; 20% treated			Clearcut with seed trees				Uniform shelterwood	
Planted species	White pine	White pine	Red oak	White oak	Pitch pine	Red pine	Red oak	White oak	White pine	Red pine
Seedlings per ha (and source) for climate period 1971–2000	253/ha (local)	NA	NA	NA	NA	168/ha (local)	NA	NA	1138/ha (local)	128/ha (local)
Seedlings per ha (and source) for climate period 2011–2040	303/ha (Barrie, ON)	425/ha (Barrie, ON)	213/ha (Central WI)	143/ha (Tillsonburg, ON)	608/ha (Eastern ON)	NA	NA	335/ha (WI)	NA	NA
Seedlings per ha (and source) for climate period 2041–2070	353/ha (Niagara Falls, ON)	425/ha (Niagara Falls, ON)	213/ha (IA)	NA	NA	167/ha (Barrie, ON)	505/ha (IA)	NA	NA	NA
Seedlings per ha (and source) for climate period 2070–2100	353/ha (VA)	NA	NA	NA	NA	NA	NA	NA	NA	NA
Total number of seedlings per ha	1260/ha	1418/ha			1783/ha				1265/ha	
Assisted Migration Strategy	Within range	Within range; range expansion			Within range, range expansion, long-distance migration				NA	

Seed sources were selected based on modeling using the SeedWhere software (McKenney *et al.* 1999) to map climate similarities between geographic regions and the projected climates at the PRF based on RCP 8.5 scenario. ON: Ontario; IA: Iowa; VA: Virginia; WI: Wisconsin

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