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Comparing long-term projected outcomes of adaptive silvicultural approaches aimed at climate change in red pine forests of northern Minnesota, USA

Jacob J. Muller, Linda M. Nagel, and Brian J. Palik

Abstract: The Adaptive Silviculture for Climate Change (ASCC) project was developed to test ecosystem-specific adaptation approaches. The first ASCC trial was installed on the Cutfoot Experimental Forest (CEF) in northern Minnesota, USA, in 2014. Three adaptation treatments (resistance, resilience, and transition), along with a no action control, were tested and compared using Forest Vegetation Simulator to determine their relative success. We compared mean annual increment (MAI) and mortality and determined how well each treatment achieved its species composition and stand structure targets. MAI was highest in the no action (3.77 ± 0.43 $m^3 \cdot ha^{-1} \cdot year^{-1}$) and lowest in the transition (1.72 ± 0.16 $m^3 \cdot ha^{-1} \cdot year^{-1}$). However, MAI for the transition treatment continually increased over time, which extended culmination age. The no action control had the highest mortality with 38.76 (±1.32) $trees \cdot ha^{-1}$ per 10-year timestep, while the resistance and transition treatments had the lowest levels at 9.36 (±0.49) and 4.19 (±0.35) $trees \cdot ha^{-1}$, respectively. Our findings highlight the relative success of the transition, which had lower mortality, greater structural diversity, and a future-climate-adapted species composition. The results from this study provide important context for adaptive silviculture aimed at climate change and offers an example of potential outcomes of these forest adaptation options.

Key words: silviculture, forest modeling, adaptive management, climate change, forest adaptation.

Résumé : Le projet de sylviculture adaptative face aux changements climatiques (SACC) a été entrepris pour tester des approches d'adaptation spécifiques aux écosystèmes. Le premier essai du projet SACC a été établi en 2014 dans la forêt expérimentale de Cutfoot (FEC) qui est située dans le nord du Minnesota, aux États-Unis. Trois traitements d'adaptation (résistance, résilience et transition) ainsi qu'un témoin non traité ont été testés et comparés à l'aide du simulateur de végétation forestière pour déterminer leur succès relatif. L'accroissement annuel moyen (AAM) et la mortalité ont été comparés entre les traitements et nous avons déterminé dans quelle mesure chaque traitement a atteint ses objectifs de composition en espèces et de structure de peuplement. L'AAM était le plus élevé dans le témoin (3,77 ± 0,43 $m^3 \cdot ha^{-1} \cdot an^{-1}$) et le plus faible dans le traitement de transition (1,72 ± 0,16 $m^3 \cdot ha^{-1} \cdot an^{-1}$). Cependant, l'AAM associé au traitement de transition a continuellement augmenté au fil du temps, ce qui a repoussé l'âge d'atteinte de l'AAM maximal. La mortalité la plus élevée a été observée dans le témoin avec 38,76 (±1,32) $tiges \cdot ha^{-1}$ par période de 10 ans, alors que les valeurs les plus basses ont été observées dans les traitements de résistance et de transition avec, respectivement, 9,36 (± 0,49) et 4,19 (±0,35) $tiges \cdot ha^{-1}$. Nos résultats mettent en évidence le succès relatif du traitement de transition qui était associée à une plus faible mortalité, une plus grande diversité structurelle et une composition en espèces adaptée au climat futur. Les résultats de cette étude fournissent un contexte important pour la sylviculture adaptative face aux changements climatiques et offrent un exemple de résultats potentiels des options d'adaptation forestière qui ont été testées. [Traduit par la Rédaction]

Mots-clés : sylviculture, modélisation forestière, aménagement adaptatif, changements climatiques, adaptation forestière.

1. Introduction

Climate change and changes in associated biotic and abiotic stressors (e.g., insects and disease, drought, wildfire) threaten the long-term sustainability of forest ecosystems and the services they provide (Dale et al. 2001; Peterson et al. 2011) and are driving a new set of complex forest management challenges. One challenge is that forest managers need to make informed management decisions today to address future climate change. This will require the best available science to help anticipate the impacts of climate change on forest ecosystems and expected outcomes of management strategies, especially novel silvicultural approaches designed to promote forest health and sustainability under uncertain future conditions (Lachapelle et al. 2003; Wright 2010). Changing management priorities and policies in the face of climate change, inadequate funding and training opportunities for adaptive management, and an overall lack of on-the-ground examples (and evidence of long-term outcomes) of adaptation strategies have all contributed to a slow response in addressing these complex challenges (Kocher et al. 2012; Kemp et al. 2015). Further, predicted

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J.J. Muller.* Department of Forest Resources, University of Minnesota, 1530 Cleveland Avenue N, Saint Paul, MN 55108, USA.
L.M. Nagel. Forest and Rangeland Stewardship Department, Colorado State University, 1472 Campus Delivery, Fort Collins, CO 80523, USA.
B.J. Palik. Northern Research Station, Forestry Sciences Laboratory, USDA Forest Service, 1831 Highway 169 E, Grand Rapids, MN 55744, USA.
Corresponding author: Jacob J. Muller (email: jacob.muller@uky.edu).
*Present address: Department of Forestry and Natural Resources, University of Kentucky, 204 TP Cooper Building, Lexington, KY 40546, USA.

future climate change, coupled with forests functioning outside their historical range of variability with respect to disturbance dynamics, suggest strategies that focus on a wide spectrum of adaptation options may be necessary to effectively implement adaptive management approaches (Hobbs et al. 2014). There is an urgent need for managers to gain a better understanding of potential long-term stand dynamics and outcomes of climate-adaptive approaches that encompass adaptive management (Janowiak et al. 2011).

The Adaptive Silviculture for Climate Change (ASCC) project was developed to address these needs by creating a network of long-term research sites that test ecosystem-specific adaptation approaches and strategies (Nagel et al. 2017). The ASCC project utilizes the Climate Change Response Framework (https://forestadaptation.org; Janowiak et al. 2014) to foster manager–scientist partnerships and develop regionally specific examples of on-the-ground adaptation approaches designed to facilitate adaptive responses to climate change (Nagel et al. 2017). In 2015, the first ASCC trial was installed on the Cutfoot Experimental Forest (CEF) on the Chippewa National Forest in northern Minnesota, USA. The trial (henceforth MN-ASCC) is located in a red pine-dominated mixed-pine forest on the southern edge of the boreal forest. Red pine (*Pinus resinosa* Aiton) forests in this region hold great ecological, social, and economic value (Ek et al. 2006; Gilmore and Palik 2006); however, these forests may be vulnerable to the effects of climate change (Handler et al. 2014; Reich et al. 2015).

The different silvicultural treatments in the MN-ASCC study correspond to a range of adaptation options that create a variety of stand structures and species compositions, each aimed at adapting to climate change in a different way (Millar et al. 2007). The treatments were developed to test and compare the efficacy of adaptation options with different goals: (*i*) to resist the effects of climate change and maintain current conditions (resistance); (*ii*) to increase resiliency by accommodating a certain level of change, but ultimately maintain the ecosystem within its natural range of variation in composition and structure (resilience); (*iii*) to transition forests to conditions better suited for future conditions by encouraging an adaptive response (transition); and (*iv*) a passive no action approach (Nagel et al. 2017). Given that this and other long-term ASCC installations are in their infancy, there is a need to gain an understanding of likely future outcomes of adaptive silvicultural strategies in the near-term to provide management and policy guidance, with simulation modeling being a useful approach.

Forest growth and yield models are an essential planning tool for assessing long-term response to silvicultural treatment and allow managers and researchers the ability to gain immediate insight into potential treatment responses. The Forest Vegetation Simulator (FVS) serves as a primary forest growth model of the USDA Forest Service and other forest management organizations and is an important tool for characterizing long-term responses to treatments, including productivity, species composition, and mortality (Crookston and Dixon 2005). FVS is a distance-independent, individual-tree forest growth and yield model that relies on a set of tree attributes, which are classified by density, forest type, diameter, and height (Stage 1973; Crookston and Dixon 2005). FVS interprets inventory data along with stand and site information to calculate current stand conditions and estimate future growth and composition. The Lake States variant of FVS (FVS-LS) contains local calibrations for forests located in northern Minnesota (Dixon and Keyser 2008). We utilized the Lake States variant here as a base model for projecting stand development and potential outcomes for each of the MN-ASCC treatments.

The overall objective of this work was to assess the potential efficacy of the MN-ASCC treatments in achieving their respective management objectives and desired future conditions (DFCs) over the next 100 years as related to stand structure, species composition, productivity, and mortality. To address this objective, we used the silviculture prescriptions for the study, designed to achieve the climate-adaptive management goals (resistance, resilience, transition, and no action), along with post-treatment data to compare treatment performance using model outputs from FVS-LS. We compared key variables from FVS output across the adaptation treatments, including mean annual increment (MAI) to allow us to assess growth patterns over time, trends in species composition over time, and mortality of trees per hectare (TPH) per simulated FVS timestep (10 years). We asked two overarching questions: (*i*) how well would each treatment meet its associated management objectives and DFCs related to structure, species composition, productivity, and mortality over time? and (*ii*) which treatment would perform the best when these key variables relative to each treatment's DFCs (i.e., structure, species composition, productivity, mortality) are combined?

2. Methods

2.1. Study site

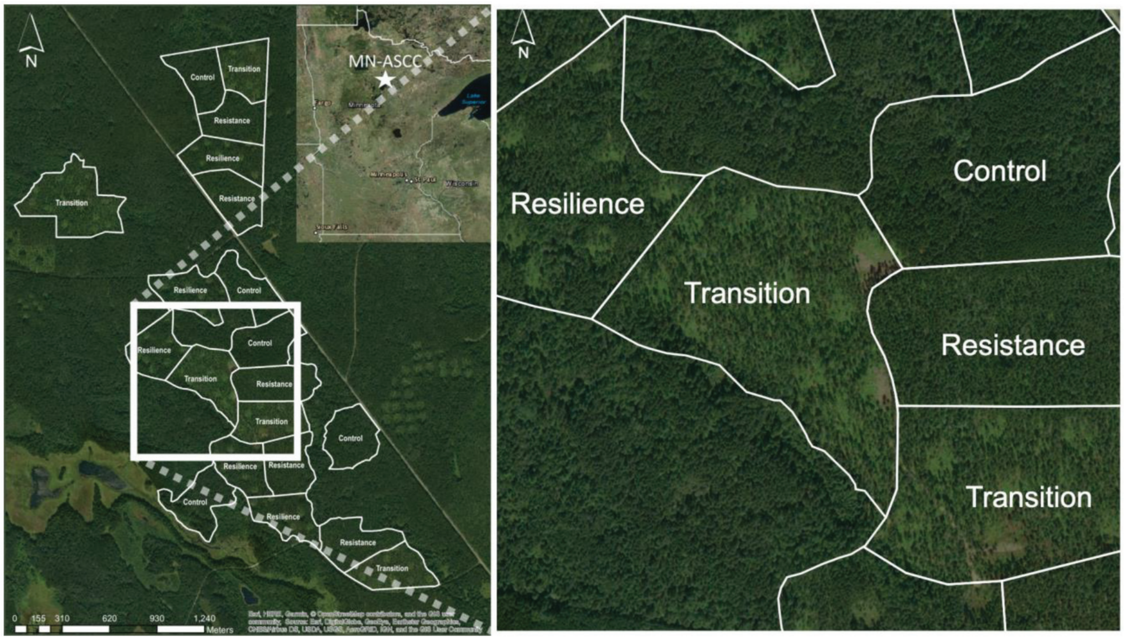
The MN-ASCC study site is located on the Cutfoot Experimental Forest (CEF) on the Chippewa National Forest in north-central Minnesota, USA, at a latitude of 47°40′N and a longitude of 94°5′W. The CEF is located within the Northern Minnesota Drift and Lake Plains section of the Laurentian Mixed Forest Province (MNDNR 2003). The forests within the CEF are classified as dry-mesic mixed woodland (type FDn33a; Aaseng et al. 2011). Across the study area, red pine comprises approximately 85% of the canopy tree basal area (BA; $m^2 \cdot ha^{-1}$), with varying amounts of jack pine (*Pinus banksiana* Lamb.) and eastern white pine (*Pinus strobus* L.). Northern red oak (*Quercus rubra* L.), paper birch (*Betula papyrifera* Marsh.), and quaking aspen (*Populus tremuloides* Michx.) are also common forest associates. Bur oak (*Quercus macrocarpa* Michx.), balsam fir (*Abies balsamea* L. Mill.), and white spruce (*Picea glauca* (Moench) Voss) are found less frequently (Muller et al. 2019). The site index for red pine is 17 m (base age 50). The average BA on the CEF is 32–41 $m^2 \cdot ha^{-1}$ with a mean diameter at breast height (1.37 m) of 32 cm. The CEF has well-drained medium to fine sandy soils developed from glacial outwash parent material (Adams et al. 2008). The entire MN-ASCC treatment area is of natural origin, with the majority of trees establishing following a fire in 1918.

The climate of the CEF is characterized by cold, long winters and a warm, short growing season. The average annual temperature at the CEF is 3.9 °C. Maximum summer temperatures can exceed 32 °C while minimum winter temperature can reach below −35 °C. The average July high temperature is 26.5 °C while the average January high temperature is −7.4 °C. The CEF has an average annual rain-equivalent precipitation of 50 to 64 cm (PRISM Climate Group 2018), while total winter snowfall ranges from 1 to 2 m.

2.2. Study design and implementation

The MN-ASCC study design (Nagel et al. 2017) involves three adaptation approaches (resistance, resilience, transition) and a no action control. These approaches were developed in June 2013 during a collaborative workshop that consisted of an expert panel comprised of scientists and managers who discussed climate-change-related forest vulnerabilities for the dry mesic mixed-pine forests in the region (FDn33a), developed site-specific management objectives and DFCs appropriate to each adaptation approach, and developed silvicultural prescriptions to meet each approach using the Forest Adaptation Resources Workbook framework (Swanston and Janowiak 2016). All four treatments were replicated across five blocks for a total of 20 treatment units (four treatments × five replicates). Each treatment unit is approximately 10 ha, while the entire study encompasses approximately 200 ha (Fig. 1). All treatments were harvested during the winter of

Fig. 1. Map showing the location of the Minnesota Adaptive Silviculture for Climate Change (MN-ASCC) project within the Cutfoot Experiment Forest, Chippewa National Forest, Minnesota, USA. Map includes all treatments (Resistance, Resilience, Transition, and No Action (Control)) with each replicated once per block across five blocks. Map visually highlighting variability in stand conditions among ASCC treatments. Map was created using ArcGIS 10.7. Map image source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.



2014–2015 on frozen ground conditions with snow cover during most of the harvesting.

Overall, the goals for the red pine forest type on the study area include maintaining low levels of mortality, sustaining productivity levels within an acceptable range for the red pine forest type and providing wildlife habitat associated with mature conifer forests in the region. All MN-ASCC treatments aim to achieve this common set of management objectives but as described below, differ in the pathways used to achieve these objectives. See Table 1 for full descriptions of management objectives, DFCs, and silvicultural treatment descriptions.

The objective of the resistance treatment for the MN-ASCC study is to maintain a red pine-dominance with a minor component of eastern white pine, jack pine, red maple (*Acer rubrum* L.), balsam fir, quaking aspen, red oak, and bur oak. Additionally, the treatment aims to maintain red pine at the lower limit of stocking according to regional stocking diagrams (Benzie 1977; Gilmore and Palik 2006), to help sustain growth during periods of drought (Bottero et al. 2017), while also maintaining red pine at 90% of total stocking (BA) and all other species at 10% or less of the total BA. To accomplish these goals, a thinning treatment was prescribed to achieve an average BA of 23–27 $m^2 \cdot ha^{-1}$ in each treatment unit. Mean post-treatment BA of the resistance treatment was 25.76 (±0.41; standard error) $m^2 \cdot ha^{-1}$ (Table 2). A second thinning entry is planned for approximately 10 years following the first entry to further reduce BA to 17–22 $m^2 \cdot ha^{-1}$, with follow-up thinning treatments to maintain stocking levels between 17 and 27 $m^2 \cdot ha^{-1}$.

The goal of the MN-ASCC resilience treatment is to maintain a red pine-dominated (50%–75% total BA) mixed conifer condition with lesser components of minor species currently found in the ecosystem. Red pine should remain above the lower limit of acceptable stocking. To achieve these goals, the resilience treatment utilized a variable density thinning approach to create 0.2 ha gaps (20% of the treatment unit) and 0.2 ha unthinned skips (20% of the treatment unit), with the remainder of the treatment (60%) thinned to a similar stocking as the resistance treatment (17–27 $m^2 \cdot ha^{-1}$). Total post-treatment stocking (pooling across matrix, gaps, and skips) of the resilience units was 20.54 (±2.27) $m^2 \cdot ha^{-1}$ (Table 2). Skips were delineated as no-cut patches with conditions similar to the no action control. The aim of the gaps was to provide higher light environments and lower overstory competition for tree regeneration. Gaps were mechanically site prepared using a grapple skidder equipped with a harrow disk attachment to expose mineral soil for planting seedlings. Gaps were planted with several species native to the ecosystem that are thought to be future-climate-adapted. These species, which were planted at a 5.5 m spacing in each gap, include jack pine, northern red oak, bur oak, eastern white pine, and red maple. The resilience prescription includes repeated thinning of the matrix to maintain basal area between 17 and 27 $m^2 \cdot ha^{-1}$, along with expanding the gaps (e.g., from 0.02 to 0.04 ha) to release established regeneration and promote further regeneration.

For the MN-ASCC site, the goals for the transition treatment include creating and maintaining structurally complex stands containing a diversity of growing conditions and to increase the abundance of future-climate-adapted tree species. The silvicultural tactics include reducing overall stand density and promoting a non-red pine dominated species composition. To accomplish this, a regeneration harvest similar to an expanding gap irregular shelterwood (Femelschlag) was prescribed (Troup 1928; Raymond et al. 2009). This entailed thinning the matrix to 14–18 $m^2 \cdot ha^{-1}$ average BA and cutting of 0.2 ha gaps (20% of the treatment unit). Total post-treatment stocking (matrix and gaps) was 9.71 (±1.04) $m^2 \cdot ha^{-1}$ (Table 2). Mechanical site preparation, as in the resilience treatment, was performed throughout the treatment stands. The transition prescription includes expanding gaps from 0.2 to 0.4 ha within 20 years of initial treatment and maintaining BA of the matrix

Table 1. Summary of the Minnesota Adaptive Silviculture for Climate Change project treatments, overarching treatment goals, management objectives, desired future conditions, and silviculture prescriptions (Rx).

		Desired future conditions and management objectives					
Treatment	Goal	Stand density	Structure	Composition	Productivity	Mortality	Rx
Resistance	Maintain relatively unchanged conditions	Stand is to be maintained over time between 17 and 27 $m^2 \cdot ha^{-1}$ BA	Even-aged, single cohort structure maintained through repeated thinning	Red pine dominated (>90%) with minor species maintained at less than 10% of total BA	High productivity with minimal variation over time	Low levels of mortality with <0.5% mortality of stems per hectare	Repeated thinning treatment promoting red pine retention
Resilience	Allow some change with an eventual return toa range of natural variation	Matrix thinned to 17–22 $m^2 \cdot ha^{-1}$ BA. Gaps thinning to 0 $m^2 \cdot ha^{-1}$ BA. Stand is to be maintained over time between 17 and 27 $m^2 \cdot ha^{-1}$ BA	Two-cohort structure maintaining even-aged structure across the matrix and new cohort in gaps	Red pine dominated (~75%) but species composition may fluctuate over time	High productivity but allowed to deviate over time	Low levels of mortality with <0.5% mortality of stems per hectare	Variable density thinning with regeneration harvest and planting in gaps. 20% of stand in 0.2 ha skips and 20% in 0.2 ha gaps
Transition	Facilitate change, and promote an adaptive response	Harvest to 14–18 $m^2 \cdot ha^{-1}$ of BA. Subsequent thinning throughout matrix to maintain 17–22 $m^2 \cdot ha^{-1}$ of BA. Gaps expanded over time	Multi-cohort structure with increasing vertical heterogeneity over time as gaps are manually expanded	Non-red pine dominated composition with increasing component of future-climate-adapted species over time	High productivity of non-pine, future-climate-adapted species	Low levels of mortality with <0.5% mortality of stems per hectare	Irregular shelterwood with expanding gaps and planting throughout with subsequent intermediate thinning
No action	Serve as a baseline for treatment comparisons	No target	No target	No target	No target	No target	Passive approach

within a range similar to the resistance and resilience treatments. Species selected for planting were based on Tree Atlas (Iverson et al. 2008) projections, Minnesota Native Plant and Suitability Guidelines, and information gathered through the collaborative workshop. Selected species included northern red oak, bur oak, red maple, eastern white pine currently found in the study area, as well as several species not currently found in the study ecosystem but have projected future suitable habitat in the region based on Tree Atlas modeling (Iverson et al. 2008). These species included bitternut hickory (*Carya cordiformis* Wangenh.), black cherry (*Prunus serotina* Ehrh.), white oak (*Quercus alba* L.), and ponderosa pine (*Pinus ponderosa*; see Muller et al. (2019) for additional details on rationale for species choice and planting procedures). Additionally, a passive no action treatment was established to provide a baseline to compare outcomes for each actively managed treatment described above.

2.3. Plot measurements

Post-treatment data was collected on 170 permanent plots (seven to 11 plots per treatment unit depending on treatment × four units per block × five blocks) located across the study area during the 2016 growing season. Location of each plot was permanently marked with overstory trees stem-mapped and measured. Each plot included a 0.08 ha macroplot, a centrally nested 0.04 ha microplot, and a series of three nested 0.004 ha subplots surrounding the microplot. Diameter at breast height (DBH; 1.3 m above base of tree) of overstory trees (DBH ≥ 12.7 cm) was measured in the 0.08 ha macroplots. Basal area of each tree (m^2) was calculated from diameter and extrapolated to the plot level ($m^2 \cdot ha^{-1}$). Total height was randomly sampled on 10% of trees in each macroplot. Trees between 8.9 and 12.6 cm DBH were measured in the 0.04 ha nested microplots. Natural regeneration of trees less than 30.5 cm in height was tallied and recorded in each of the nested 0.004 ha subplots. Planted seedling survival data (trees$\cdot ha^{-1} \cdot$species^{-1}; described in Muller et al. 2019) from MN-ASCC plot measurements were collected on all transition plots (matrix and gap) and resilience gap plots for 3 years post-planting (2015–2018).

2.4. FVS-LS projections and data analyses

The Forest Vegetation Simulator-Lake States variant (FVS-LS; download date June 20, 2018; https://www.fs.fed.us/fvs/software/complete.php; Dixon and Keyser 2008) was used to simulate development of the MN-ASCC treatments. The core of the FVS-LS model was originally based on the TWIGS model (Miner et al. 1988) and refined in 2006 to improve individual tree growth and yield projections (Dixon and Keyser 2008). The FVS-LS model assumes (as of 2021) a static future climate not capable of accommodating climate change projections within the framework of the model. Analyses were performed with the understanding that the FVS-LS model will not capture climate factors and one must accept the model's limitations. However, the value that FVS provides in simulating potential future stand structures and species compositions, for us, outweighs its limitations in application.

Post-treatment inventory data was aggregated in a Microsoft (MS) Access database and organized in an FVS-ready format. FVS accommodates three levels of data input: stand-level, plot-level, and tree-level. Stand-level data was constructed in an FVS stand list table to describe site index, elevation, location, and total treatment area. Plot-level data was constructed in a FVS plot list table to describe treatment subgrouping and plot size. Lastly, tree-level data was constructed in an FVS tree list table from data recorded for each tree and includes species, diameter at breast height (DBH), height, and live crown ratio. A location file (.loc) was created to import the data files from MS Access into the FVS Suppose User Interface (Dixon 2002). Red pine site index estimates from plot measurements were used to calibrate the FVS

Table 2. Summary of post-treatment (pre-forest vegetation simulator simulation) average unit basal area (BA) and quadratic mean diameters (QMD) by treatment with standard error (SE) describing variation.

ASCC treatment	Subtreatment	No. of plots (170 total)	Starting BA (±SE) ($m^2 \cdot ha^{-1}$)	QMD (±SE) (cm)
Resistance	Total	35	25.76±0.41	35.25±3.8
Resilience	Total	55	20.64±2.27	26.3±17.42
	Gap	15	0.54±0.29	1.33±2.68
	Matrix	25	25.03±0.27	38.29±4.38
	Skip	15	44.62±2.8	35.63±2.84
Transition	Total	45	9.71±1.04	20.45±12.64
	Gap	15	0.12±0.07	0.7±0.93
	Matrix	30	14.71±1.07	31.75±3.53
No action (control)	Total	35	40.52±1.52	32.84±3.53

model (10-year iterations) for the Chippewa National Forest (FVS geographic location code = 903).

Planted seedling data collected from plot measurements were manually input into the FVS tree list based on survival levels for each species after the first three growing seasons (Muller et al. 2019). Natural regeneration from plot data was manually specified in FVS-LS using the keyword extension for the partial establishment model (Dixon 2002). The base FVS-LS stand density index (SDI-based) mortality model (Dixon 2002) was used for treatment projections.

The silvicultural treatments were constructed in FVS by creating unique groupings for each treatment prescription (i.e., resistance, resilience, transition, and no action). Additionally, subgroupings were created for the resilience and the transition treatments to account for structural variability in those treatments. In total, there is one group for resistance that represents the thinned matrix, three subgroupings for the resilience (thinned matrix, gaps, skips), two subgroups for the transition (thinned matrix, gaps), and one grouping for the no action treatment. Each grouping and subgrouping of plots were modeled, weighted (per area according to the treatment design), and then summed to calculate treatment-level results (see Table 2 for total number of plots in each treatment grouping). Output data was extrapolated and weighted based on area within each treatment subgroup across the treatment unit.

Novel species used in the MN-ASCC experiment presented unique modeling considerations in FVS, as species projections rely purely on empirical growth and yield data from the region (or local FVS variant). Because there is a lack of empirical information for ponderosa pine in the Great Lakes region, we utilized red pine species growth and yield equations, given the similar physiology and growth, and silvical characteristics (e.g., reproduction, moisture tolerance, shade tolerance, competitive ability) between the two species (Richardson 2000). The red pine equations used for simulating ponderosa pine include the relative SDI (stand density index) function, mortality sensitivity, diameter, and SI (site index) curves for simulating tree growth. Given the geographic proximity of white oak, black cherry, and bitternut hickory (all found within 50–100 km of the CEF), no species modifications were applied to the FVS growth and yield equations.

Management actions in FVS were initiated for each treatment to reflect the MN-ASCC silviculture prescriptions using post-initial treatment plot data from 2015 (Table 1). Simulations for each treatment began in 2016 (reflecting the immediate post-treatment data collection year) with 10-year timesteps for each iteration. Simulations were performed for 110 years (2016–2126) and included a total of eleven 10-year timesteps.

To simulate the resistance treatment over time, a thinning treatment was initiated at year 2025 (reflected in timestep 2026) to reduce BA to 17 $m^2 \cdot ha^{-1}$. Subsequently, thinning was applied every other timestep (i.e., every 20 years) to maintain BA between 17 and 27 $m^2 \cdot ha^{-1}$ throughout the simulation period.

FVS simulations for the resilience treatment included a thinning of the matrix 20 years after initial treatment (2036), once average BA exceeded 27 $m^2 \cdot ha^{-1}$. Repeated thinning occurred every other timestep to maintain BA between 17 and 27 $m^2 \cdot ha^{-1}$. Gaps were "expanded" in 2035 by initiating an overstory removal on 20% of the matrix to simulate a gap expansion of 0.2 to 0.4 ha. The matrix, as well as the maturing cohort in the gaps, were repeatedly thinned every 20 years to maintain matrix BA between 17 and 27 $m^2 \cdot ha^{-1}$. Skips were designated and maintained as unthinned components of each resilience treatment unit.

FVS simulations for the transition treatment included an initial matrix thinning treatment to a BA of 14 $m^2 \cdot ha^{-1}$. Gaps were "expanded" in timestep 2036 by initiating an overstory removal on 20% of the matrix to simulate a gap expansion of 0.2 to 0.4 ha. Gaps were thinned in year 2056 to a residual BA of 14 $m^2 \cdot ha^{-1}$. In addition to a thinning treatment in year 2056, gaps were again expanded by initiating an overstory removal of an additional 30% of the existing matrix area. Gap expansions (overstory removals) were performed while maintaining the new cohort of trees (developed from artificial regeneration). By the end of the simulation, 20% of the treatment unit was maintained as intact, but thinned matrix, while the rest of the stand area was included in the original and expanded gaps. The entire treatment (gaps and matrix) was thinned again in timesteps 2076 and 2096 to maintain total treatment BA between 14 and 18 $m^2 \cdot ha^{-1}$. Artificial regeneration (using the original suite of future-climate-adapted species with the same seedling densities; see Muller et al. 2019) was manually initiated following each gap expansion treatment.

Following FVS simulation, the full list of simulated trees (stratified by treatment grouping) was exported from FVS and aggregated into a single long-data format csv file. Stand and stocking reports were generated and used to quantify variables for treatment comparisons including average treatment BA ($m^2 \cdot ha^{-1}$), quadratic mean diameter (QMD; cm), mean annual increment (MAI; $m^3 \cdot ha^{-1}$), merchantable standing volume ($m^3 \cdot ha^{-1}$; using Scribner log rules), and mortality (TPH). For this study, we compared structure, composition, productivity, and mortality of each treatment to determine how well each treatment performed relative to one another. Given disparities in species compositions across treatments, which created significant differences in potential growth increments between deciduous and conifer species, merchantable volume was used as a proxy for treatment productivity instead of MAI. MAI was used to quantify stand growth and culmination age. Results are presented in *per hectare* units of average treatment outputs to allow for comparison.

A "yes–no" matrix was developed to assess the overall achievement of treatments meeting their prescribed DFCs and management objectives. The matrix includes questions asking whether the treatment achieved it management goals related to stand density and structural targets, species composition and productivity (MAI and standing volume) targets, along with acceptable mortality targets.

2.5. Statistical analysis

We used repeated measures analysis of variance (ANOVA), using the statistical package R (R Core Team 2015), to analyze response variables (i.e., mean annual increment (MAI), merchantable volume, merchantable volume removed, and mortality) for each timestep for each treatment simulation. The nlme package (Pinheiro et al. 2012) was used to develop linear mixed effects model (lme) for response variables and allow for treatment comparisons, including the no action treatment. Random effects included "plot" and "year" for each model. We tested the random effects by comparing the lme model to a model fitted with only the fixed effects (excluding random effects). Because random effects were not included in the fixed-effects-only model, the gls function in the nlme package was used to fit the model. ANOVA was used to compare the fixed-effects-only model and the full models for each response variable. The lsmeans package (Lenth 2013) was used for post hoc testing of MN-ASCC treatments. Tukey's HSD was used to test for statistical difference among treatments. A significance threshold of alpha = 0.05 was used to identify differences.

3. Results

3.1. No action projections

The no action is a passive management approach and provides a baseline comparison to the three adaptation treatments. Growing freely over time, the starting BA in year 2016 was 41.72 (±1.03; one standard error) $m^2 \cdot ha^{-1}$ and the ending BA in year 2116 was 53.49 (±1.12) $m^2 \cdot ha^{-1}$. Average quadratic mean diameter (QMD) increased over the simulation period from 30.66 (±0.43) cm in 2016 to 40.87 (±0.48) cm in 2116. Diameter distributions based on stand density (TPH and BA; supplementary Fig. S1[1]) show a mature red-pine-dominated stand at the end of the simulation period. Size and species distributions depict a range of size classes, where shade-tolerant species (e.g., balsam fir, red maple) occupy the smaller size classes, while red pine and eastern white pine occupy the larger size classes.

Over the simulation period, stand density shifts to larger size classes (>75 cm; Fig. S1[1]). There was minimal variation in species composition over the simulation period (Fig. S1[1]). Red pine remained the dominant species throughout the simulation period, ranging from 72.34% (±3.8 standard error) of total BA in 2016 to 69.23% (±3.9) BA in 2116. Eastern white pine was the second most abundant species (ranging from 8.42% (±1.9) of total BA in 2016 to 12.12% (±2.2) BA in 2116), followed by northern red oak. Other minor species (i.e., balsam fir, red maple, jack pine) were maintained at less than 3% total BA throughout the simulation period (Fig. S1[1]).

3.2. Resistance treatment projection

The first FVS simulated reentry (Year 2025) in the resistance treatment reduced average treatment BA from 27.23 (±1.21; one standard error) $m^2 \cdot ha^{-1}$ to 19.42 (±0.92) $m^2 \cdot ha^{-1}$. Over the next 100 years, average treatment BA had minimal variation (20.32 ± 1.18 to 25.34 ± 1.32 $m^2 \cdot ha^{-1}$; Fig. 2A). Repeated thinning was performed every two timesteps in FVS (20 years) to maintain this level of BA (Fig. 2A). In the first entry in 2015, an average 124 (±4.66) $m^3 \cdot ha^{-1}$ of merchantable volume was removed from the treatment, while subsequent thinning treatments removed an average of 27 (±1.43) $m^3 \cdot ha^{-1}$ of merchantable volume. QMD increased from 37.83 (±1.2) cm in 2016 to 57.32 (±3.21) cm in 2116 (Fig. 2B). Average mortality increased from 7.32 (±1.54) trees$\cdot ha^{-1}$ per timestep (over 10 years) in 2016 to 20.21 (±5.32) trees$\cdot ha^{-1}$ per timestep in 2116 (Fig. 2C).

There was minimal variation in species composition in the resistance treatment (supplementary Fig. S2[1]). DBH distributions based on treatment density (TPH and BA) reflect a single cohort stand with density shifting to larger size classes (>75 cm) in the latter simulated timesteps (2116; Fig. S2[1]). Red pine remained the dominant species throughout the simulation period, ranging from 87.54% (±3.2) of total BA in 2016 to 91% (±4.5) BA in 2116. Eastern white pine had the second highest relative dominance, ranging from 5.43% (±2.1) of total BA in 2016 to 8.12% (±3.2) BA in 2116. Minor species in the resistance treatment (i.e., balsam fir, red maple, jack pine, red oak) were maintained at less than 5% total BA throughout the simulation period (Fig. S2[1]).

3.3. Resilience treatment projections

The initial average treatment unit BA of the resilience treatment (averaged across the matrix, skips, and gaps) was 21.23 (±1.21) $m^2 \cdot ha^{-1}$ (Table 2). Treatment BA had minimal variation over the simulation period, ranging from 21.23 (±4.21) $m^2 \cdot ha^{-1}$ in 2016 to 26.23 (±4.82) $m^2 \cdot ha^{-1}$ in 2116. The average unit BA increased to 30.23 (±2.3) $m^2 \cdot ha^{-1}$ in 2036 before the thinning treatments and gap expansions were applied in the same simulation period (Fig. 3A). This thinning removed 35.23 (±6.21) $m^3 \cdot ha^{-1}$ across the resilience matrix. A total of four thinning treatments were applied every other timestep (20 years) to maintain BA under 25 $m^2 \cdot ha^{-1}$. Gap expansion removed 20% of the matrix overstory and resulted in a spike in merchantable volume removed. The average merchantable volume removed during each entry was 23.67 (±7.21) $m^3 \cdot ha^{-1}$ per timestep. Quadratic mean diameter increased from a starting diameter of 25.65 (±8.21) cm in 2016 to a final QMD of 52.54 (±4.54) cm in 2116 (Fig. 3B). Mortality across the treatment increased as the stand aged, with an average of 17.43 (±4.32) trees$\cdot ha^{-1}$ of mortality per timestep (over 10 years) in 2016 to 32.54 (±8.76) trees$\cdot ha^{-1}$ per timestep in 2116 (Fig. 3C).

Resilience treatment species compositions varied over time, as planted gaps maintained a diverse species composition over the simulation period (supplementary Fig. S3[1]). Diameter distributions of TPH and BA reflect multi-cohort stands being maintained over time (Fig. S3[1]). As the stand matured over time, stand density shifted to larger size classes (>75 cm) in the last growing period (2116; Fig. S3[1]). Red pine remained the dominant species throughout the simulation period, ranging from 78.34% (±4.43) of total BA in 2016 to 67.54% (±7.65) BA in 2116. Eastern white pine remained the next abundant species throughout the simulation period, ranging from 10.67% (±3.65) of total BA in 2016 to 15.87% (±4.97) BA in 2116. Species planted in the gaps (20% of treatment area) maintained a similar level of BA throughout the simulation period. Eastern white pine increased in total BA, while red oak declined over time. All other species (e.g., red maple, jack pine, bur oak) maintained similar levels of relative BA from 2016 to 2116 (Fig. S3[1]).

3.4. Transition treatment projections

The starting average BA for the transition treatment (averaged across both matrix and gaps) was 9.71 (±1.04) $m^2 \cdot ha^{-1}$ (Table 2). Average treatment BA varied over the time, ranging from 23.56 (±3.21) $m^2 \cdot ha^{-1}$ in 2056 to 15.65 (±2.44) $m^2 \cdot ha^{-1}$ in 2066, following thinning and gap expansion (Fig. 4A). The first entry (of a total of four entries) occurred in 2036, reducing the stand BA to 15 $m^2 \cdot ha^{-1}$ and expanding gaps (to release regeneration) from 0.2 ha to 0.4 ha. This treatment resulted in an average 35.90 (±8.43) $m^3 \cdot ha^{-1}$ per timestep of merchantable volume removed from the treatment

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjfr-2021-0097.

Fig. 2. Resistance treatment boxplots across each timestep (2016–2116) of (A) basal area (BA), (B) quadratic mean diameter (QMD, cm), and (C) mortality. Boxes span the upper and lower quartiles while the lines represent the maximum and minimum values. Black horizontal lines represent the median value.

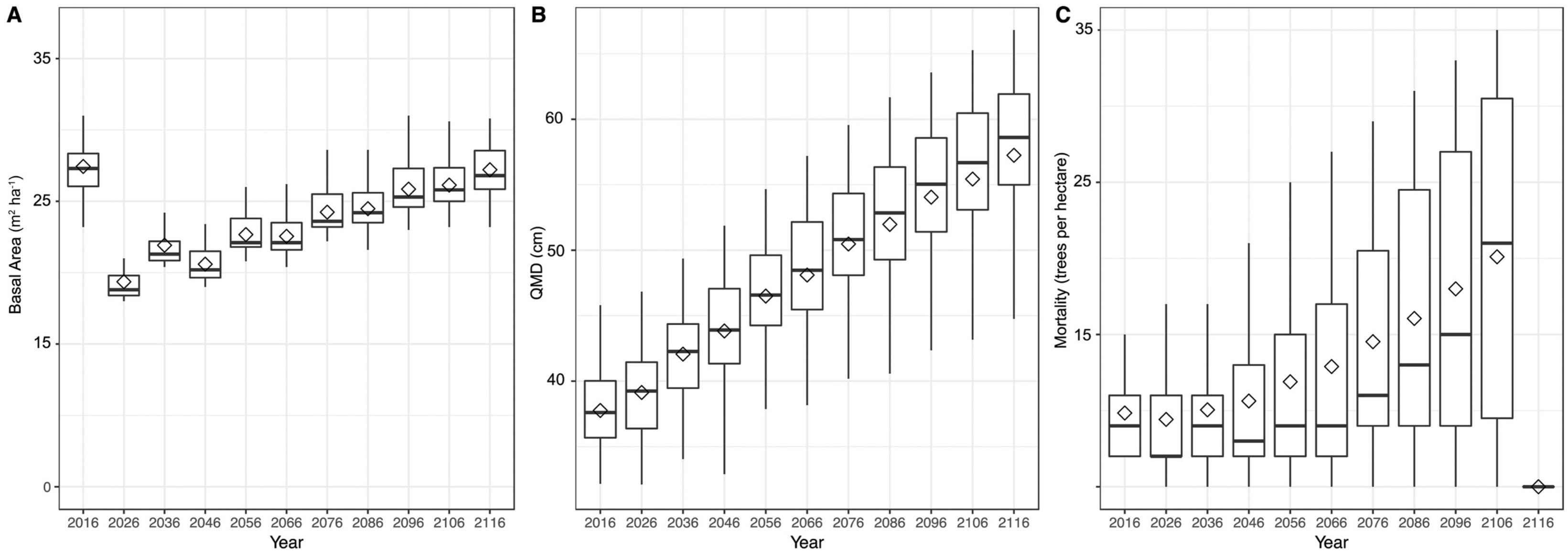
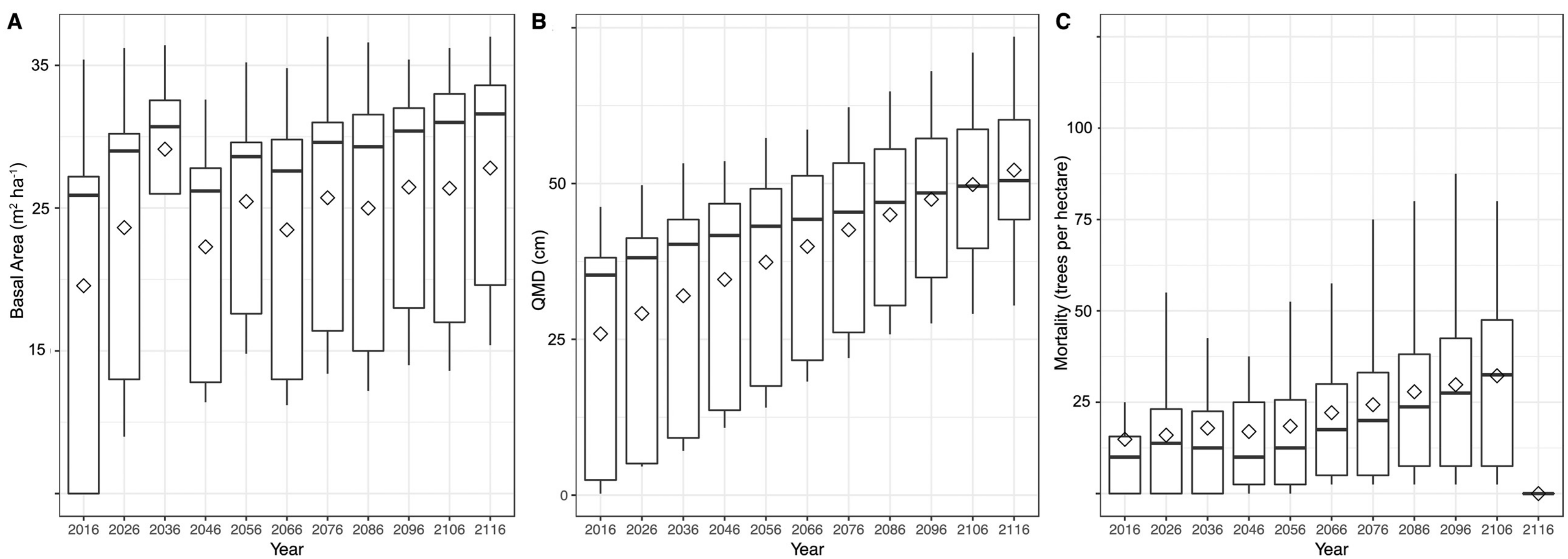


Fig. 3. Resilience treatment boxplots across each timestep (2016–2116) of (A) basal area (BA), (B) quadratic mean diameter (QMD, cm), and (C) mortality. Boxes span the upper and lower quartiles while the lines represent the maximum and minimum values. Black horizontal lines represent the median value.



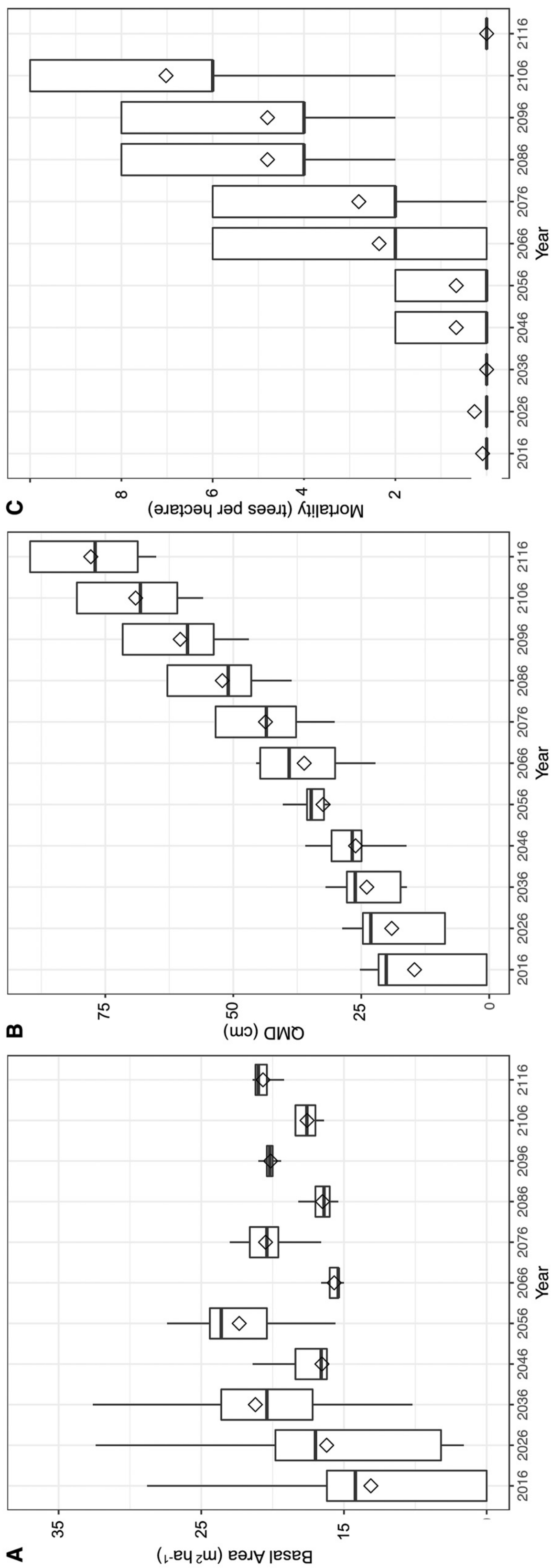


Fig. 4. Transition treatment boxplots across each timestep (2016–2116) of (A) basal area (BA), (B) quadratic mean diameter (QMD, cm), and (C) mortality. Boxes span the upper and lower quartiles while the lines represent the maximum and minimum values. Black horizontal lines represent the median value.

units. In 2056, gaps were again expanded (overstory removal of 20% of the matrix) that resulted in a spike of merchantable volume removed from the transition units. These two treatments (2036 and 2056) removed an average of 68.54 (±6.32) $m^3 \cdot ha^{-1}$ per timestep of merchantable volume across all treatment units. At the end of the simulation period (110 years), 20% of the original matrix remained intact. Additional thinning treatments were applied in 2076 (removing an average of 63.22 (±4.10) $m^3 \cdot ha^{-1}$) and in 2096 (removing an average of 52.59 (±3.43) $m^3 \cdot ha^{-1}$). QMD increased from a starting diameter of 27.54 (±4.3) cm in 2016 to 51.22 (±5.78) cm in 2116 (Fig. 4B). Mortality ranged from 0.34 (±0.02) trees$\cdot ha^{-1}$ during the first simulation period to 8.74 (±2.4) trees$\cdot ha^{-1}$ during the final simulation period (Fig. 4C).

Species composition in the transition treatment was highly variable over time. BA of future-climate-adapted species shifted to larger diameter classes, while red pine BA was significantly reduced (supplementary Fig. S4[1]). High numbers of trees were maintained in the smaller diameter size classes throughout the simulation period as a result of planting future-climate-adapted species following each gap expansion in years 2036 and 2056. During the first simulation period red pine was the dominant species (63.43% ±5.23% of total BA). Over time, following gap expansion, transition treatment species composition shifted away from red pine. Ponderosa pine became an increasingly greater component of the treatment units (25.05% ±6.45% of total BA). Eastern white pine became the dominant species (reflected as relative BA) across the treatments, increasing to 15.32% (±4.74%) of total stand BA in 2116. Other less abundant species (i.e., red maple, red oak, bur oak, white oak, black cherry, bitternut hickory) had minimal variation over the simulation period, with each maintaining between 4% and 9% of total treatment BA (Fig. S4[1]).

3.5. Treatment comparisons

Treatment performance was compared using mean annual increment (MAI), merchantable standing volume, merchantable volume removed, and mortality (Table 3). Overall, MAI was highest in the no action (3.77 ± 0.43 $m^3 \cdot ha^{-1} \cdot year^{-1}$) and lowest in the transition treatment (1.72 ± 0.16 $m^3 \cdot ha^{-1} \cdot year^{-1}$; Table 4; Fig. 5A), reflecting the differences in amount of growing stock. The resistance and resilience treatments had no significant differences in MAI, while both were less than the no action and greater than the transition (Table 4). Over time, MAI increased across treatments as thinning intensity increased (Fig. 5A). MAI for the transition treatment increased over time, while the no action and resistance treatments increased initially and began to decrease in year 2046. MAI was highly variable across the resilience and transition treatments as evidenced by a wide range of values resulting from spatial variability in stand density and structure (i.e., gaps, skips, matrix). General trend lines indicate a decline in MAI (culmination age) in the no action, resistance, and resilience treatments, while the culmination age for the transition continues to extend (increasing MAI) over the simulation period (Fig. 5A).

Merchantable volume over the simulation period varied significantly among the treatments and over time (Table 3). Merchantable volume averaged 544.54 (±5.93) $m^3 \cdot ha^{-1}$ per timestep in the highest density condition (no action), while the transition treatment had an average merchantable volume of 124.47 (±6.04) $m^3 \cdot ha^{-1}$ per timestep (Table 4). Merchantable volume increased over time for each treatment, with the no action exhibiting the largest increases. The transition treatment had significantly more volume removed over the simulation period despite being maintained at the lowest overall density. The resilience treatment had the lowest removal of volume, at 8.64 (±1.49) $m^3 \cdot ha^{-1}$ per timestep.

Mortality also varied significantly among treatments (Table 3). The no action treatment had the highest levels of mortality, with 38.76 (±1.32) trees$\cdot ha^{-1}$ per timestep. The resistance and transition treatments had the lowest levels of mortality at

Table 3. Summary of repeated measures ANOVA for mean annual increment (MAI), merchantable volume, merchantable volume removed, and mortality for forest vegetation simulator projections.

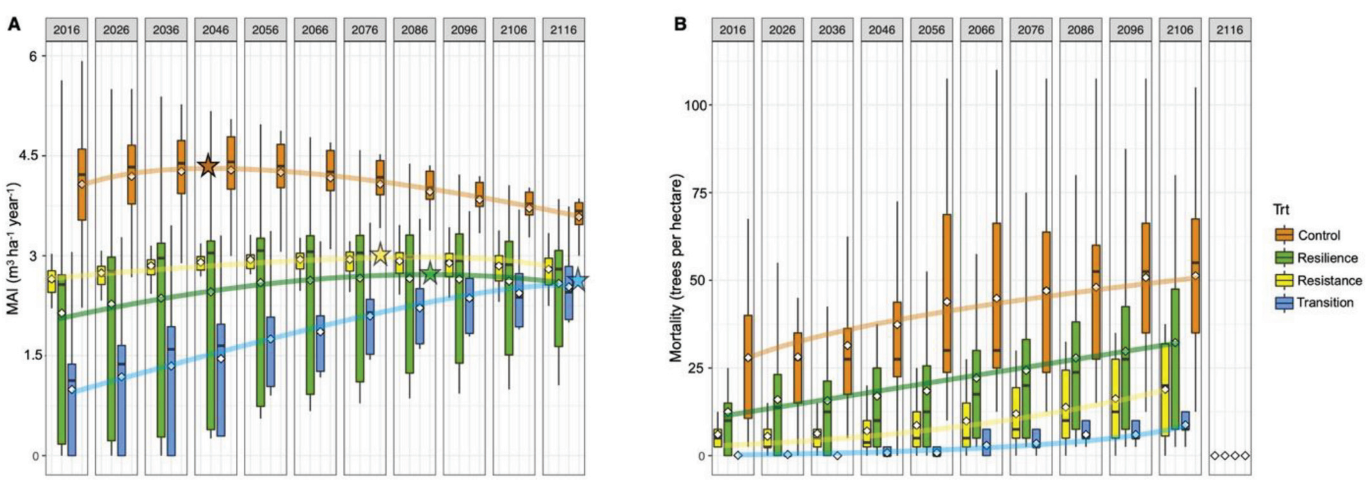
Source of variation	df	Stand MAI		Merchantable volume		Merchantable volume removed		Mortality	
		F	*P*	*F*	*P*	*F*	*P*	*F*	*P*
ASCC Rx (Treatment)	3	489.53	<0.001	1150.3	<0.001	57.86	<0.001	285.28	<0.001
Year	10	54.87	<0.001	378.4	<0.001	59.08	<0.001	12.09	<0.01
Treatment × Year	30	50.46	<0.001	36.56	<0.001	29.3	<0.001	0.735	0.53

Table 4. Mean (±SE) attributes (mean annual increment (MAI), merchantable cubic volume, merchantable cubic volume removed, and mortality) from FVS projections of the MN-ASCC treatments with standard error (SE) describing variation.

ASCC treatment	Subtreatment	Average MAI (±SE) ($m^3 \cdot ha^{-1} \cdot year^{-1}$)	Average merchantable volume (±SE) ($m^3 \cdot ha^{-1}$ per timestep)	Average merchantable volume removed (±SE) ($m^3 \cdot ha^{-1}$ per timestep)	Average mortality (±SE) ($trees \cdot ha^{-1}$ per timestep)
Resistance	Total	2.66±0.16b	241.16±2.56b	18.23±1.66b	9.36±0.49a
Resilience	Total	2.34±0.21b	356.84±7.21b	8.64±1.49a	19.81±1.15b
	Gap	0.73±0.59	292.21±4.34	10.53±1.46	3.31±0.31
	Matrix	2.79±0.21	339.73±4.06	10.27±1.51	21.04±0.91
	Skip	3.95±0.75	567.61±10.27	—	46.91±1.35
Transition	Total	1.72±0.16a	124.47±6.04a	26.13±3.82c	4.19±0.35a
	Gap	0.98±0.82	91.51±5.19	—	4.49±0.35
	Gap Expansion 1	2.07±0.88	121.47±6.39	31.60±5.94	2.32±0.41
	Gap Expansion 2	2.2±0.8	143.34±6.21	34.95±6.14	1.87±0.32
	Matrix	1.98±0.56	158.12±3.09	25.65±3.64	0.88±0.25
No action (control)	Total	3.77±0.43c	544.54±5.93c	—	38.76±1.32c

Note: Letters adjacent to values (within the same column) indicate comparisons of treatments (resistance, resilience, transition, no action) within a given variable.

Fig. 5. Boxplots showing all four treatments across each timestep (2016–2116) of (A) mean annual increment (MAI) and (B) mortality. Boxes span the upper and lower quartiles while the lines represent the maximum and minimum values. Black horizontal lines represent the median value. Lines reflect general trends in the data. Stars in subfigure "A" correspond to estimated culmination age for each treatment.



9.36 (±0.49) $trees \cdot ha^{-1}$ per timestep and 4.19 (±0.35) $trees \cdot ha^{-1}$ per timestep, respectively (Table 4; Fig. 5B). The resilience treatment had relatively high levels of mortality (compared to resistance and transition) at 19.81 (±1.15) $trees \cdot ha^{-1}$ per timestep. Mortality increased over time in each of the treatments (Fig. 5B).

Desired species assemblages were maintained over time in each treatment. The no action and resistance treatments had similar species compositions in pre- and post-FVS projection stands (Fig. 6), while the resilience and transition treatments shifted towards a much more heterogeneous species composition, which includes future-climate-adapted species (Fig. 6). Overall, at year 2116, the resistance treatment achieved all of the stated management objectives, except for the mortality target. Similarly, the resilience treatment also achieved all of the stated management objectives except for the mortality target. The transition treatment, however, achieved all stated management objectives including mortality (Table 5).

4. Discussion

Managing forests to control stand structure and species composition are key elements of most silviculture prescriptions (Naumann

Fig. 6. Bar charts showing proportional (0.0–1.0) basal area ($m^2 \cdot ha^{-1}$) by species for each treatment across simulated timesteps (2016–2116), where (A) is resistance treatment, (B) is resilience treatment, (C) is transition treatment, and (D) is the no action control. Colors represent individual species.

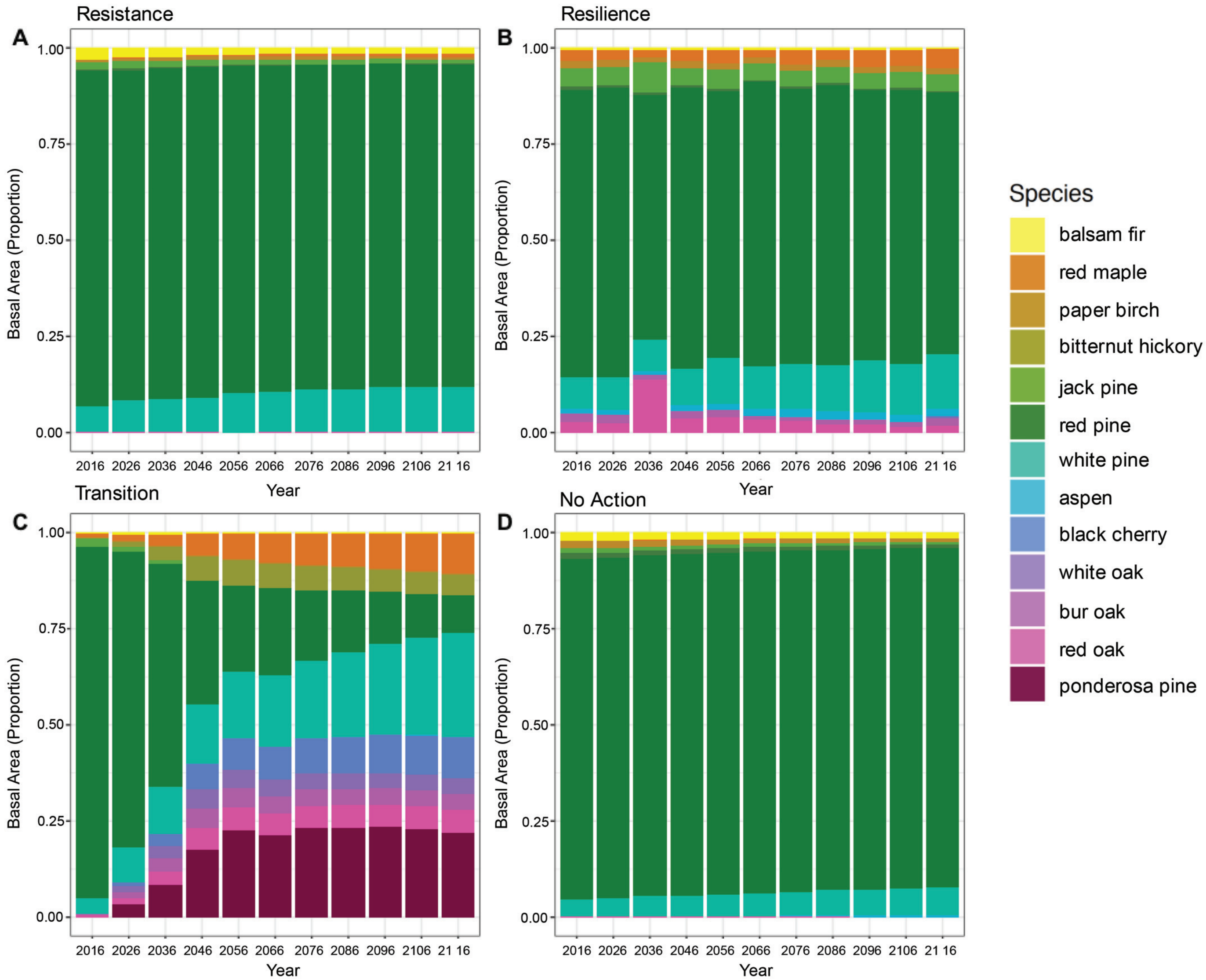


Table 5. Treatment performance matrix reflecting overall achievement in meeting desired future conditions (DFCs) and management objectives.

	Did treatments meet their prescribed DFCs and management objectives in terms of:				
ASCC treatment	Stand density	Structure	Species composition	Productivity	Mortality
Resistance	Yes	Yes	Yes	Yes	No
Resilience	Yes	Yes	Yes	Yes	No
Transition	Yes	Yes	Yes	Yes	Yes

et al. 1992). Over the past 100 years of pine forest management in the northern Great Lakes, silvicultural prescriptions have typically focused on shortening rotation ages, single-cohort structures, and red-pine-dominated species compositions (Woolsey and Chapman 1914; Palik et al. 2020). This management approach has typically satisfied objectives for producing timber, though often at the expense of forest ecosystem functions (Puettmann and Ek 1999) including, potentially, adaptation to climate change. Recently, however, this timber-focused management paradigm has begun to change and shift toward a more ecologically based approach that considers sustainability of a greater suite of ecosystem services, particularly on public lands (Palik and D'Amato 2019).

Climate change poses additional challenges to ensuring forest health and productivity in the Great Lakes region of North America (Handler et al. 2014; Duveneck et al. 2014). Management approaches that promote heterogeneity may help to increase ecosystem resilience to climate change and promote adaptive responses. Furthermore, options that promote future-climate-adapted species and heterogeneous stand structures create a range of growing conditions that will facilitate an adaptive response and bolster long-term sustainability (Galatowitsch et al. 2009; Frelich and Reich 2010; Iverson et al. 2017). The MN-ASCC adaptive silviculture treatments incorporate adaptation approaches to promote future-climate-adapted species compositions. These silvicultural treatments reflect a range of management approaches, both well-practiced and novel for this region, to achieve management objectives in the context of a changing climate.

The overall objective of this study was to use forest growth simulations to assess the potential efficacy of the MN-ASCC treatments in achieving their respective management objectives and DFCs over the next 100 years as related to stand structure, species composition, productivity, and mortality. We asked two overarching questions: (*i*) how well would each treatment meet its associated management objectives? and (*ii*) which treatment would perform the best when these key variables relative to each treatment's DFCs are combined? To answer the first question, we examined each treatment individually. After 100 years of simulation, the resistance treatment achieved the stated management objectives for structure, species composition, and productivity. However, the desired future conditions for mortality were not met, though overall mortality remained relatively low (0.6% per year). The objectives that were met were achieved through repeated thinning entries to control species composition and basal area. After multiple entries, red pine was maintained at 90% of total BA within the resistance units. All other species were maintained at less the 10% of total BA. As climate continues to change, the effort needed to maintain these management objectives will likely increase (Millar et al. 2007). Eventually, the costs of managing these stands may exceed the revenues generated from timber sales as multiple entries may be required to control composition and competition (Harris et al. 2006). The ASCC resistance treatment typifies timber-focused management in the region through periodic thinning to regulate stand density to optimize growth of trees. The approach has the added benefit of providing greater access to soil moisture to these trees during drought (Bottero et al. 2017). The FVS outputs provided an opportunity for measuring potential stand projections under current management approaches, and the potential future effort needed to achieve management objectives.

After 100 years of FVS simulation, the resilience treatment also achieved the stated management objectives for structure, species composition, and productivity. Again however, the mortality target was not met. Desired conditions for the resilience treatment consist of a multi-cohort, red pine-dominated forest (50%–75% BA), with a sustained composition (<30%) of other associated species native to this forest type. To achieve these management objectives, a variable density thinning was used to increase structural heterogeneity through the creation of gaps and retention of skips as bookends for the thinned matrix. Over time, thinning treatments and gap expansion resulted in management objectives and DFCs being met. Basal area was maintained (on average) within the desired levels over the simulation period. Not surprisingly, productivity (measured as merchantable volume removed) was markedly higher during the gap expansion. Mortality was highly variable over time, while higher levels of mortality occurred in the skips as growing space was limited and exceeded the upper limits of a fully stocked red pine stand for the region, triggering competition-induced mortality in the FVS model. Future-climate-adapted species planted in gaps provided the majority of species diversity, which aligns with treatment DFCs. Species diversity and structural heterogeneity are important forest adaptation elements (Swanston and Janowiak 2016); previous research on species diversity and forest resiliency support this adaptation approach (DeClerck et al. 2006; Aerts and Honnay 2011). Heterogeneous structures are better able to accommodate moderate levels of disturbance and allay the impacts of large disturbances (Drever et al. 2006). If an insect or disease outbreak were to occur in the resilience treatment, it would likely impact only a few species, while others could potentially survive and maintain forest structure and function.

Over time, the transition treatment achieved all of the stated management objectives. The transition treatment maintained high species diversity and a non-red pine dominated composition. The low density stands favored large tree retention, while the spatially patchy canopy structure promoted spatial heterogeneity. The approaches used in the transition treatment approximates natural mixed-severity forest disturbance regimes that often create heterogeneous structures (Palik and D'Amato 2019). The transition treatment utilizes this approach while favoring future-climate-adapted species, including novel species not currently found on the CEF, but are predicted to have increasing suitable habitat as the climate shifts to warmer conditions (Muller et al. 2019). QMD increased sharply over each simulated timestep as the planted cohort matured. This is likely due to the increased growing space for individual trees. Further, natural mortality remained low throughout the simulation period as stand density remained low, reducing competition and self-thinning. Future-climate-adapted species (e.g., eastern white pine, ponderosa pine, black cherry, bitternut hickory, red oak, bur oak, white oak) continually increased over the simulation period while red pine gradually decreased over time and was maintained as a minor component of the stand in year 2116 (Fig. 6C), as reflected in the transition DFCs. All management objectives for the transition treatment were met through the implementation of an irregular shelterwood approach.

To answer our second question, which treatment (i.e., resistance, resilience, transition) would perform the best at achieving its stated management objectives and DFCs, we combined each individual management objective relative to the treatment's stated goals and compared across treatments. Overall, repeated thinning (or gap expansions) helped achieve management objectives and DFCs for each treatment as modeled through FVS. The no action, resistance, and resilience treatments did not achieve target levels of stand mortality of less than 0.5% of total stems per timestep. The transition treatment maintained low levels of mortality (<0.5% of total stems) throughout the simulation period, the only treatment to achieve this objective. Considering productivity, the transition treatment had significantly greater volume removed at each entry than all other treatments. We observed no significant differences in productivity between the resistance and resilience treatment, though the resistance treatment initially had greater volume removed due to the initial thinning to reduce BA from 27 to 17 $m^2 \cdot ha^{-1}$. Mortality was highly variable across treatments, while all treatments had significantly less occurrence of mortality than the no action treatment. The transition treatment had significantly lower natural mortality as overall stand density remained low.

Our results allow further quantitative examination of the potential outcomes for each treatment, how well they might achieve associated DFCs, and provide a mechanism to compare long-term performance through FVS projections. Our results also demonstrate that the low-density, irregular shelterwood approach utilized in the transition treatment significantly prolonged the culmination age for MAI (Fig. 5A). Transition MAI continued to increase throughout the simulation period while the resistance and resilience treatment MAI plateaued and began decreasing in 2056 (Fig. 5A). Previous research has shown that thinned stands delay culmination age of MAI compared to unthinned stands (Stinson 1999; D'Amato et al. 2010). The FVS projections for this study support these findings and indicate that the transition treatment may be managed on a longer rotation while remaining productive. By extending the rotation age, forest managers may be able to meet multiple management objectives through active, adaptive forest management strategies while promoting mitigative management approaches aimed at climate change (e.g., carbon markets). While mitigative management approaches are fairly novel and many research needs exist on the blending of adaptive and mitigative management (e.g., carbon storage), managing for extended rotations in these northern Lake States forest types may offer one option for a robust climate-focused management plan.

5. Conclusions

Climate change will likely cause adverse effects on forest productivity and sustainability of ecosystem functions in many regions and forest types, including red pine dominated ecosystems of the western Great Lakes region (Handler et al. 2014). As such, it will become increasingly important for managers to consider adaptive management approaches to meet objectives and sustain forests and the ecosystem services they provide. This study has shown that management objectives associated with the MN-ASCC adaptive silviculture approaches are attainable, at least in simulated outcomes. A notable finding of this study is the relative success, compared to the other treatments, of the transition treatment at meeting the articulated DFCs, including greater timber (volume) production and lower mortality due to lower stand densities, and greater structural diversity combined with a future-climate-adapted species composition. These results support low density and variable density stand management with expanding gaps (as reflected in the transition treatment) as a viable option for red pine management, while also promoting an adaptive response over time.

Results from this study provide context for adaptive silviculture aimed at climate change and offer examples of applicable adaptation options for the study ecosystem. While our results offer insight, we acknowledge the limitations of using an empirical forest growth model to predict complex processes associated with adaptive management and climate change. While a Climate–FVS (Crookston et al. 2010) option is available for the intermountain West, a climate-modified version is not currently (2021) available for eastern variants, as these forested regions typically have more complex and diverse species assemblages and less certain tree and forest responses to climate change (Fei et al. 2017). There is a critical need to develop these climate sensitivities into eastern FVS variants or other dynamic forest growth models to support and enhance future management efforts and long-term planning. Had a climate-sensitive FVS model been available for use at the time of this project, we may have seen differences in tree growth and species compositions over time as some species will inevitably fare better in future climate conditions while others will fare worse. Given this, the transition treatment may have performed even better at meeting its management goals and DFCs relative to the other treatments when using a climate-sensitive forest growth model. The value of forest growth models cannot be understated; however, it will be important to maintain the MN-ASCC treatments and monitor the long-term progress and outcomes to confirm these conclusions.

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Competing interests

We declare no competing financial, professional, or personal interests that might have influenced the performance or presentation of the work described in this manuscript.

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