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Balancing multiple forest management objectives under climate change in central Wisconsin, U.S.A.

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ABSTRACT

Forest managers must balance multiple objectives and consider tradeoffs when developing a management plan. Complex interactions between successional dynamics and natural disturbances make it challenging, especially when decisions play out under the deep and dynamic uncertainties associated with climate change. Here we explored a suite of management strategies to maximize multiple management objectives and minimize tradeoffs under future climate projections and quantified the greatest sources of uncertainty. We used a spatially-explicit forest simulation model (LANDIS-II) to simulate the effects of wind, management, and climate change in central Wisconsin and calculated benefits and tradeoffs among six management objectives (maximize aboveground carbon (C), soil C, harvested C, C stored in species of cultural importance to the Menominee tribe, tree diversity, and age diversity). We found that uneven-aged management achieves more ecosystem benefits (except for harvested C) than the other harvest strategies, but it was the business-as-usual harvest scenario that minimized tradeoffs among objectives. Climate change made it more difficult to store C in soils and have diverse forests and the management strategies we considered were unable to regain these lost benefits. Climate change reduced harvested C and C stored in culturally-important species, but the management strategies were able to at least partially compensate for this effect. The uncertainty surrounding the climate projections generated the largest variation in all benefits except harvested C. Managers seeking to maximize benefits and minimize tradeoffs should consider a range of silvicultural strategies while recognizing that climate change may shrink the operating space for achieving foresters' management goals.

1. Introduction

Managing forest ecosystems for multiple ecosystem services is a wicked problem – a complex problem with multiple potential solutions (DeFries and Nagendra, 2017). Managers and other stakeholders must balance multiple, often competing objectives and come to consensus on the best ways to manage a dynamic forested landscape (Bradford and D'Amato, 2012; Diaz-Balteiro and Romero, 2008). This may require managers to explicitly consider tradeoffs, e.g. between maximizing harvest yield and carbon sequestration (e.g. Bourque et al., 2007; Bottalico et al., 2016) and how those tradeoffs will change as a function of management practices, succession, and natural disturbances. Although it has always been a struggle for managers to meet multiple objectives, managers today must balance objectives that have deep uncertainties associated with them. Deep uncertainty encompasses conditions in which decision makers do not know (or do not agree upon) the range of

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key drivers, inputs, or future conditions, the relationship between actions and consequences, and how to evaluate the alternative outcomes (Lempert et al., 2003). Deep uncertainty can emerge, for example, when climate change is considered. Recent and future changes in climate may introduce new stressors and create novel forest conditions and disturbance regimes. Also, the range of possible climate futures is large and may disproportionately affect some objectives more than others. Finally, changes in societal demands for timber and other forest-based ecosystem services are exceedingly hard to predict. Individually and collectively, these deep uncertainties complicate the ability to manage forests to meet multiple objectives sustainably.

Current decision support tools are limited in their ability to address multiple tradeoffs and nonlinear responses under deep uncertainty because of computational challenges (Lempert and Collins, 2007; Quinn et al., 2017). Analyzing how different time horizons, climate futures, natural disturbances, input parameters, and management strategies affect multiple objectives can become intractable quickly (Lempert and Collins 2007; Keller and McInerney 2008; Mcinerney et al. 2012; Quinn et al., 2017). For example, (Schwenk et al., 2012) combined simulation modeling with multi-criteria decision analysis (MCDA) to show that more intensive harvesting enhanced bird biodiversity; the positive enhancement of early seral species exceeded the declines in late seral species. However, they were able to simulate only 42 stand-alone plots and compare only three objectives (C storage, timber production, and bird biodiversity) due to computational limits. Without capturing the landscape context in which the plots are located, without considering disturbance regimes, and without simulating climate change, these types of analyses may not translate well to fragmented landscapes or landscapes where climatic changes are expected to have a large effect either directly on growth or indirectly on disturbance regimes. Furthermore, most tradeoff analyses have focused on two (Seidl et al., 2007), three (e.g. (Kline et al., 2016; McCarney et al., 2008; Schwenk et al., 2012), or four objectives (Fürstenau et al., 2007; Hennigar et al., 2008). Ideally, tradeoff analysis would evaluate the full range of objectives used in decision making, including metrics of timber production (biomass and volume removed), above and belowground C storage, tree diversity, bird diversity, animal diversity, endangered species, cultural benefits, recreation, and many others (e.g. Eyvindson et al., 2018).

Bradford and D'Amato (2012) approached this challenge by developing a simple, flexible tool that allows a manager to quickly calculate the benefits of each objective and the tradeoffs between two objectives. Using this framework, benefits are the degree to which an objective is achieved. Tradeoffs are a measure of the disparity in the ability to equally achieve both objectives; values are higher when achieving one objective requires sacrificing another. Both benefit and tradeoff metrics are normalized (i.e. scaled from 0 to 1), making it straightforward to compare objectives with different orders of magnitude, such as timber harvested and biodiversity.

We combined tradeoff analysis with simulation modeling to evaluate the influence of management practices under climate, model, and disturbance uncertainty on forest management objectives. Our framework leverages high-performance computing to combine tradeoff analysis with simulation modeling, thereby providing the opportunity to compare different future management scenarios, testing sensitivity to input parameters, and comparing a range of climate scenarios—all the while considering the spatial and temporal complexity of current and future forest landscapes.

We used a spatially explicit forest simulation model (LANDIS-II) to simulate the effects of wind, silvicultural treatments (e.g., harvesting), and climate change on six key management objectives related to carbon storage (aboveground C, soil C, C stored in species of cultural importance (i.e. white pine, sugar maple, butternut and serviceberries), timber harvesting (harvested C), biodiversity (compositional diversity (i.e. Shannon's index of tree species diversity) and age diversity. Of these, silvicultural treatments are an important lever for maintaining these objectives while mediating the effects of climate and disturbance but is unclear if they will remain effective in the future and whether some objectives are likely to be more impacted than others. To address this, we asked: Which management strategies maximize benefits and minimize tradeoffs of these objectives, even under alternative climate and wind scenarios? We also explored the sources of uncertainties in estimating these benefits and tradeoffs.

We focused on central Wisconsin because a range of forest management practices are commonly used in this region, including clearcutting, group selection, and thinning, but climate change may require a shift in these management practices over the long term. Recent climate projections suggest that the average annual temperature in Wisconsin will increase by 5 °C (averaged across 44 global circulation models and RCPs) over the next hundred years (Lucash et al., 2019), which may lengthen the growing season and lower soil moisture availability if the increases in precipitation are not able to keep pace with the projected increases in evapotranspiration. Boreal species are projected to decline in this region under climate change (Iverson et al., 2019; Olson et al., 2021; Scheller and Mladenoff, 2005), threatening important timber and recreational resources. The potential loss of species in this region is of serious concern to forest owners. For example, the Menominee Indian Tribe of Wisconsin maintains highly productive forests with 33 tree species (Mausel et al., 2017) and relates the health of the environment to the health of the Menominee people (Dockry et al., 2016). However, current management practices in the upper Midwest may fail to maintain current species composition through the end of the century under climate change (Duveneck and Scheller, 2016; Lucash et al., 2017). To address this concern, models may be useful to support decision-making and facilitate co-management of forest resources under future climate change.

2. Methods and materials

2.1. Study area

Our study area encompasses ~97,000 ha, defined by the outer boundary of the Lakewood district of the Chequamegon-Nicolet Forest in northeastern Wisconsin (Fig. 1). Elevation averages > 1200 m above sea level and the landscape contains rolling outwash plains and an abundance of small lakes (Wisconsin Department of Natural Resources, 2022). Climate in this region is continental with warm summers and cold, snowy winters (Kottek et al., 2006). Average monthly temperature ranges from −10 °C in January to 20 °C in July, based on analysis of gridded weather observations for our study landscape from 1979 to 2015 (Abatzoglou, 2013). Mean annual precipitation is 79 cm. Soils are predominantly well-drained loam over sandy outwash, loamy sand till, or drift (Wisconsin Department of Natural Resources 2022). Minor soil types in the region include moderately well-drained silt loam, well-drained sandy loam, well-drained fine sandy loam, and excessively drained sand. Soil parent materials are glacially-derived, often forming kame moraines from glacial meltwater and till deposition.

This landscape is diverse, given its location near the nexus of northern hardwoods and boreal forests. The most common forest type is maple/beech/birch (comprising 51 % of the landscape), which includes sugar maple (*Acer saccharum* L.), red maple, (*Acer rubrum* L.), and American beech (*Fagus grandifolia*). The coniferous forest type of white *(Pinus strobus* L.*)*, red *(Pinus resinosa* Ait.), and jack *(Pinus banksiana* Lam.) pines is scattered throughout the landscape, comprising 19 % of the total area. Aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) occur throughout (15 % of the study area) and dominate in the northeastern and southeastern portion of the landscape. Oak *(Quercus spp.)* forests dominate in the eastern portion of the landscape. Boreal species include paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides)*, and black spruce (*Picea mariana* (Mill.).

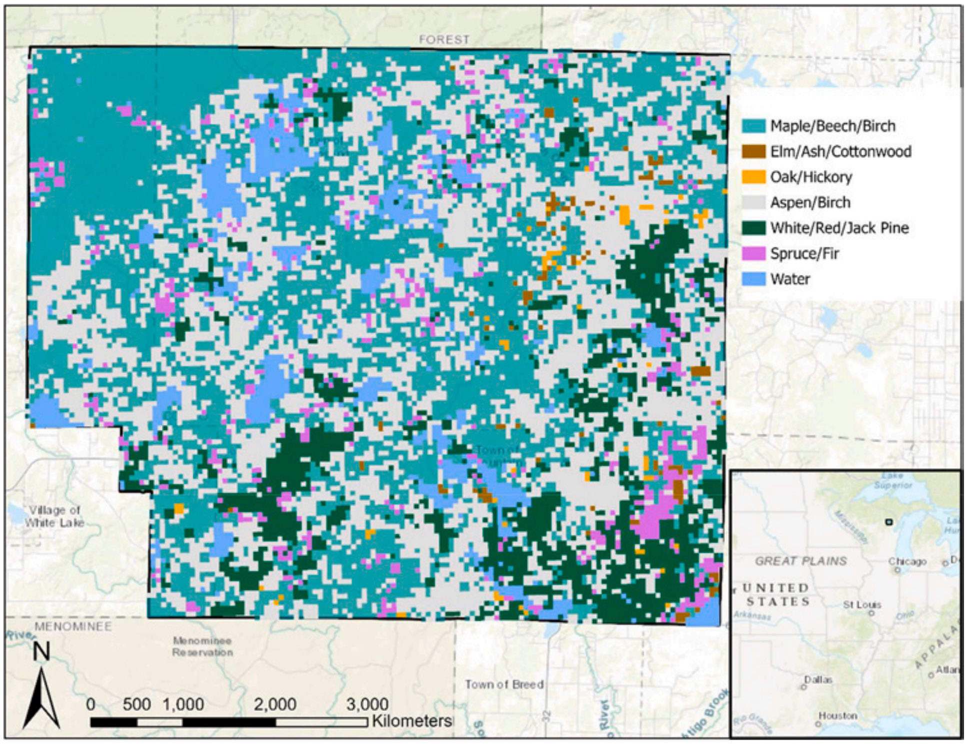

Fig. 1. Vegetation types in the Lakewood district of the Chequamegon-Nicolet Forest in northeastern Wisconsin. This map is the output from the LANDIS-II model at time = 0, which we derived from the forest inventory and analysis data (Bechtold and Patterson, 2005), as described in Lucash et al. (2019). The thumbnail insert indicates the location of the landscape in the United States.

2.2. Forest succession and C dynamics

We simulated changes in aboveground live C, soil C, biomass removed through timber harvest, and biodiversity under climate and wind scenarios using LANDIS-II, a forest landscape and disturbance model (Scheller et al., 2007). LANDIS-II is a spatially-explicit, raster--based simulation model with a landscape composed of interconnecting raster cells. Each cell (1 ha) contains information about the presence or absence of tree species and their associated ages (i.e. species-age cohorts). Each raster cell is assigned to a climate region within which climate is assumed to be homogenous. Forest successional dynamics are projected by simulating cohort growth, competition, reproduction/establishment, and mortality, as dictated by climate and life history attributes such as shade tolerance, seed dispersal, ability to sprout vegetatively, and longevity.

We used the Net Ecosystem Carbon and Nitrogen Succession (NECN) extension (v 6.2.1) of LANDIS-II v7.0 to simulate forest succession for 100 years at a 1 ha resolution (Scheller et al., 2012, 2011). NECN simulates both aboveground (e.g., growth, mortality, regeneration) and belowground processes (e.g., decomposition and N mineralization) within LANDIS-II and therefore can simulate landscape-level changes in species composition as a property of climate, succession, and disturbance. NECN simulates the growth of leaves, wood, fine roots, and coarse roots of each species-age cohort on each raster cell on a monthly basis. It tracks monthly above and belowground biomass based on species-specific life history attributes (e.g., longevity, shade tolerance), cohort age, competition (i.e. the biomass of other cohorts relative to the amount of maximum potential biomass), climate (i.e. air temperature, precipitation), and soils (e.g. drainage, soil moisture, and nitrogen availability). It simulates tree mortality caused by senescence (continuous loss of leaves and branches) and age (which accounts for the higher levels of mortality as a cohort approaches its life expectancy). The NECN extension also simulates regeneration via seeds or vegetative resprouting using life history attributes (e.g., age to sexual maturity, effective and maximum seed dispersal distances), temperature, water availability, and competition for light (Scheller et al., 2007).

The NECN extension also simulates C and N cycling in the vegetation, detritus, and soil (Scheller et al., 2011, 2012). Decomposition rates are a function of litter quantity, quality (e.g., leaf C/N ratios and lignin content), and soil conditions (e.g., soil moisture, temperature, and soil texture), using the algorithms from the CENTURY soil model v 4.5 (Parton et al., 1994, 1988). The updated N cycling algorithms (Lucash et al., 2014) allow trees to become N-limited if soil N is insufficient to meet the demands of growth. The NECN extension also calculates regeneration as a function of growing degree days (GDD), minimum January temperatures, and soil moisture using algorithms from LINKAGES (Pastor and Post, 1988) and available light.

LANDIS-II requires a map of species composition and species' age to initialize the model. To create a map of initial conditions, we used maps of forest type, species ranges, and stand age to stratify the random assignment of USDA Forest Inventory and Analysis plots (Burrill et al., 2018) to approximate the species composition, biomass, and age structure found in the current landscape (Lucash et al., 2019). Specifically, a randomly-selected, representative FIA plot with the same forest type–species-age class was chosen for each raster cell on the landscape. We included 37 tree species in our map, choosing the most dominant species in the FIA database, but some rarer species, such as serviceberries (*Amelanchier* spp.), were included based on their cultural importance to the Menominee. The Chequamegon-Nicolet Forest shares a boundary with the Menominee Nation, which has a long history of sustainable forest management practices (Dockry et al., 2016) and cultural use of trees for basket weaving and other traditional arts (Mausel et al., 2017). Details about the creation and validation of the species composition map can be found in Lucash et al. (2019). We obtained parameters for NECN from available datasets and a full description of NECN parameterization and calibration for this landscape are outlined in Lucash et al. (2019) and found on GitHub (https://github.com/LANDIS-II-Foundation/Project-Menominee-2016).

2.3. Climate scenarios

LANDIS-II requires input maps of homogenous climate subregions for computational efficiency. Climate subregions were defined using a geostatistical analysis of historical data (1979–2010) to identify the spatial extent of autocorrelated climate data within the study area, and then a spatial cluster analysis to determine the optimal spatial configuration of climate sub-regions based on historical temperature and precipitation data (Lucash et al., 2019). The resulting climate input map contained seven subregions, within each of which the climate was considered to be homogenous.

We simulated a total of seven climate time series with all simulations starting from the same initial conditions. For climatic conditions representative of the recent historical period, we calculated daily temperature and precipitation from the University of Idaho gridMET 4 km daily gridded observational analysis for each climate region from 1979 to 2010 (Abatzoglou, 2013). Data for this "historical" climate scenario were randomly selected, one calendar year at a time, from this dataset to create a climate stream corresponding to the full length of the 50-year LANDIS-II run. To simulate future climate change from 2000 to 2050, we selected six future climate scenarios from the MACAv2-METDATA ensemble (Abatzoglou and Brown, 2012) to roughly span the range of projected average temperature and precipitation over the study region during the growing season (Lucash et al., 2019; Olson et al., 2021). The selected models and IPCC emissions scenarios were MRI RCP4.5 (less warming), bcc-csm1-1 RCP4.5 (moderate warming + wetter, warm-wet), MIROC-ESM RCP4.5 (near ensemble median), CCSM4 RCP4.5 (moderate warming + drier, warm-dry), CSIRO-Mk3-6-0 RCP8.5 (high warming + wetter, hot-wet), and HadGEM2-ES365 RCP8.5 (high warming + drier, hot-wet). A detailed description of the climate scenarios is outlined in Olson et al. (2021).

2.4. Wind scenarios

Wind events are the predominant disturbance in the upper Midwest U.S. (i.e. Minnesota, Wisconsin, Michigan, Frelich, 2002), with events ranging in scale from single tree blowdowns to intense, widespread events, like tornados and derechos. Severe windstorms (>70 % overstory mortality) have a return interval ranging from 500 to 1200 years in the upper Midwest (Canham and Loucks, 1984; White and Host, 2008), but return intervals that include all wind events are seldom quantified. Also, most projections suggest that the annual frequency of tornadoes will continue to increase under climate change (Diffenbaugh et al., 2013; Gensini et al., 2014), suggesting that windstorms may become an even more important driver of long-term changes in forests. Given the uncertainty of current and future wind regimes, we examined a suite of four wind scenarios for each climate change scenario (4 wind scenarios * 7 climate scenarios = 28 simulations). We used the Base Wind Extension v3.0 (Scheller and Domingo, 2003) to simulate small-moderate patches of microburst wind disturbance, ranging from 1 to 45,000 ha in size. In this extension, wind disturbance is age-dependent, with the highest mortality in the oldest cohorts (Mladenoff and He, 1999). Base wind was calibrated under historic climate to simulate the mean annual area disturbed in the region (191 ha, Zhang et al., 1999; Frelich 2002; White and Host 2008). We also simulated a scenario with 20 % more wind area disturbed, one with 20 % less area disturbed, and one where we tested the effects of excluding wind. Although wind was an important source of mortality in our study, spatially interacting with management and climate via vegetation dynamics across the landscape, wind was considered a background disturbance.

2.5. Harvest scenarios

We simulated five different harvesting scenarios for each climate scenario (5 harvest scenarios * 7 climate scenarios = 35 simulations). The Biomass Harvest extension v.3.0 (Gustafson et al., 2000) was used to simulate forest management across the landscape. Harvesting is controlled by prescriptions targeted at specific forest ages and types (e.g. clear-cutting of red pine) while specifying the harvest rate (e.g. 0.04 % per decade) to regulate the area harvested. The prescription also specifies how much biomass is removed from which species and ages within a forest stand and allows stands to have complete (clear-cutting) or partial cohort removal (thinning). The stand map for the landscape was supplied by the USDA Forest Service (John Lampereur, pers. comm); this map delineates the boundaries where individual harvesting prescriptions can occur.

The baseline harvest scenario represented current forest management practices based in the Lakewood district of the Chequamegon-Nicolet Forest (John Lampereur, pers. comm); we calibrated acres harvested with an annual harvest rate of 0.26 % of the total landscape, distributed (non-exclusively) at the stand scale across four principal harvest prescription types, including clearcutting, group selection, and thinning treatments (Supplementary Figure S1). Keeping the area thinned constant, we also simulated scenarios with 20 % more harvested area, one with 20 % less area harvested, and one where we tested the effects of excluding harvest. Finally, we simulated harvesting at the current rate of area harvested but using either only clearcutting (even-aged) or group selection (uneven-aged).

2.6. Parameter uncertainty scenarios

Given that projections of forest change are riddled with uncertainty in input parameters and model formulations, we explored how parameter quantification determines species' climatic envelopes and how they might change with climate change. In LANDIS-II, the primary successional response to climate change is via the effect of temperature on cohort regeneration (Xu et al., 2009), especially over centennial time scales (Xu et al., 2012). Mortality is also a determinant of successional trends, although disturbance is generally regarded as distinct from climatic envelopes, and we controlled these via our scenarios of wind and harvesting (above). Within our framework, growing degree days (GDD, Pastor and Post, 1988) are the largest temperature determinants of the probability of regeneration; soil moisture is also limiting although it is indirectly linked to temperature (Scheller et al., 2005; Xu et al., 2012). The minimum January temperature also limits regeneration, although this effect is limited to rare winters with exceptionally low temperatures and is expected to decline as temperatures warm. Based on these assumed model sensitivities, we tested three scenarios of parameter (GDD) uncertainty: 1) baseline conditions representing the accepted literature values of minimum and maximum growing degree days (GDD), 2) 20 % higher values for maximum GDD and 3) 20 % lower values for maximum GDD.

2.7. Objectives and metrics

We focused on five objectives at the end of the simulation, including aboveground C, soil C, C associated with culturally-important species (i.e. white pine, sugar maple, butternut, and serviceberries), Shannon's diversity index, and age diversity (Fig. 2). We also calculated the total harvested C across the 50-year simulation.

Based on the methodology published by Bradford and D'Amato (2012), we used this formula to calculate benefits for each of the five objectives for each simulation:

$$\text{Benefits for objective A} = \frac{A\ observed\ \ - A\ minimum}{A\ maximum - A\ minimum}$$

where A_{observed} is the observed value of objective A for each simulation. The values of A_{minimum} and A_{maximum} are computed for objective A across all 420 simulations. Benefits are normalized, ranging from 0 to 1, to control for the large differences in magnitude between objectives (e.g.

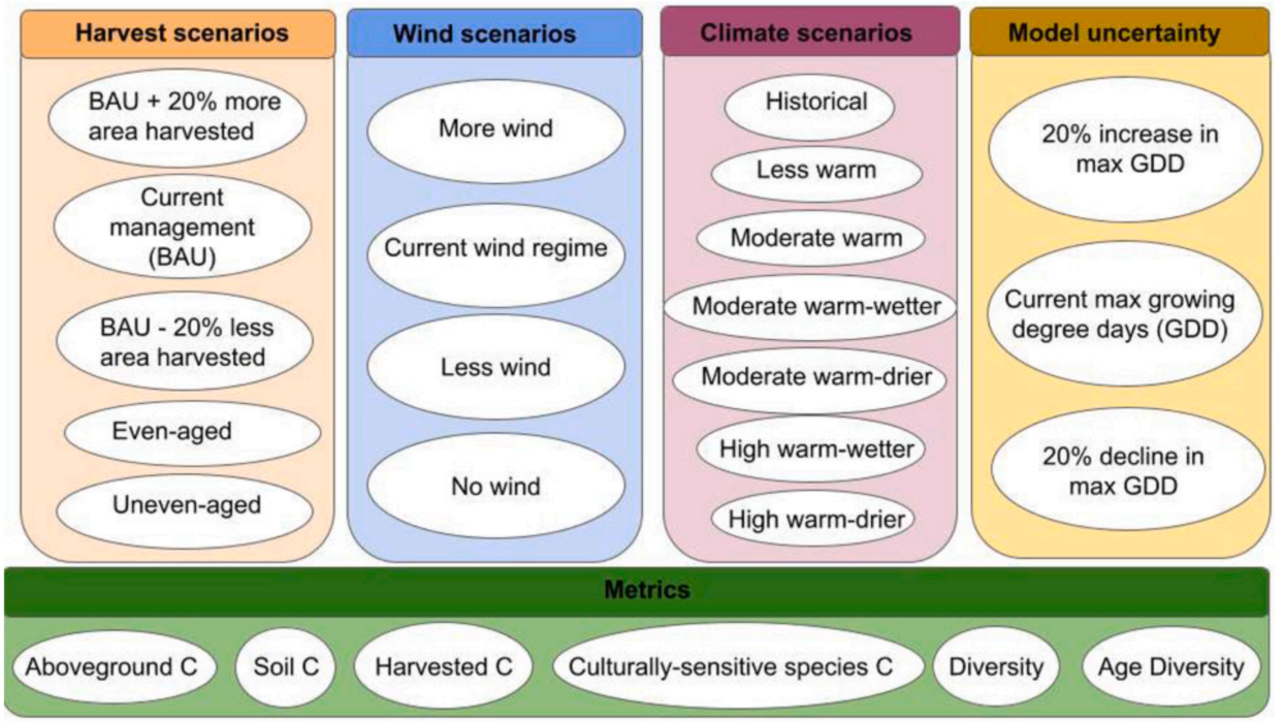

Fig. 2. Scenario design for the simulations. The LANDIS-II forest simulation model was run with five harvest scenarios, four wind scenarios, seven climate scenarios, and three model parameter scenarios. Six model outputs were analyzed with benefit and tradeoff analysis, including aboveground carbon, soil C, harvested C, C stored in species of particular importance to the Menominee, Shannon's index of tree diversity, and tree age diversity.

Shannon diversity index and aboveground C). The ideal outcome for any given scenario is to achieve high benefit scores for all objectives. We also calculated tradeoffs between each pair of objectives, recognizing that there may be high benefits for one objective at the expense of another objective. We assumed that the identity line or 1:1 line between the two benefits on a 2-D Cartesian coordinate system represented the conditions when the benefits for both objectives are equal, i.e., zero tradeoffs (Fig. 3). We used the following formula to calculate tradeoffs, because it calculates the Euclidean distance from the 1:1 line of the two benefits:

$$\text{Tradeoffs between objectives A and B} = \text{abs}(\text{Benefit A} - \text{Benefit B}) \times \frac{1}{\sqrt{2}}$$

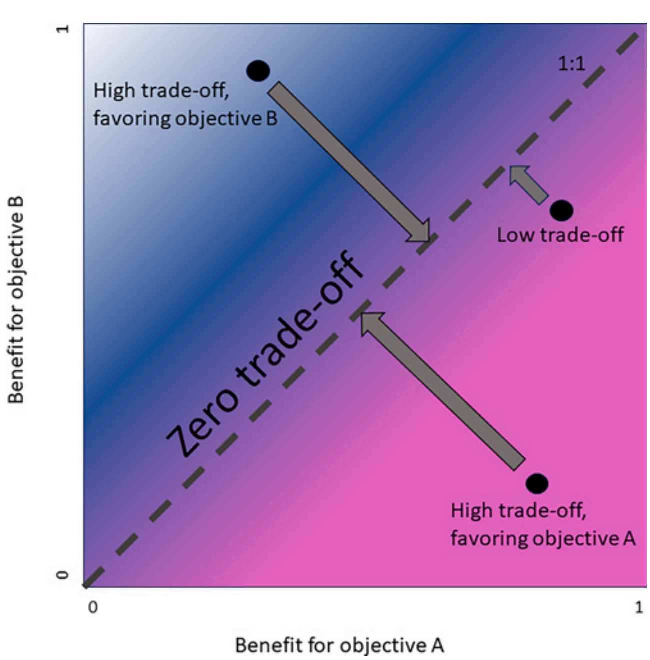

Fig. 3. Trade-off is calculated as the Euclidean distance from the 1:1 line, where the benefit of objective *A* equals the benefit of objective *B* (redrawn from Bradford and D'Amato, 2012).

2.8. Analysis of scenarios

Overall, we simulated the Lakewood district (96,691 ha) at a 1 ha resolution for 50 years (2000–2050). In total, we ran 420 landscape simulations (4 wind scenarios * 7 climate change scenarios * 5 management scenarios * 3 different GDD parameters = 420). Although it is common to run hundreds of non-spatial simulations, researchers often run only 25–100 simulations with a spatially-explicit forest landscape simulation model due to computational limits (e.g. Lucash et al., 2022; Olson et al., 2021). Specifically, in our 420 spatially-explicit simulations, over 96,736 cells were tracked at monthly to annual timesteps, depending on the model variable. The model was adapted to run under Linux (LANDIS-II was originally developed for Windows) so the model could be run on a high-performance research cluster. This, combined with automating the production of configuration files for each ensemble member made it possible run the large number of simulations described here, which allows us to more fully explore the multidimensional space of drivers, management practices, and metrics that managers consider in their decision-making.

3. Results

3.1. Variation in objectives across all scenarios

Aboveground carbon ranged from 8,204 g m^{-2} (BAU plus 20 %, less wind, hot-dry climate, lower GDD) to 106,664 g m^{-2} (uneven-aged silviculture, no wind, less warming, and higher GDD). Soil carbon was highest under uneven-aged management, ranging from 12,341 (more wind, hot-dry climate, and lower GDD) to 16,308 g m^{-2} (no wind, less warming, higher GDD). Harvested C and C stored in culturally-sensitive species were lowest under uneven-aged management (no wind, moderate warming and wetter, and lower GDD) and highest under BAU plus 20 % (more wind, less warming, and higher GDD). Species diversity was lowest in the hot-dry climate scenarios with BAU plus 20 %, more wind, and 20 % lower GDD; it was highest in the baseline climate scenarios with uneven-aged management, more wind, and higher GDD. Age diversity was lowest in the baseline climate scenarios with BAU plus 20 %, more wind, 20 % higher GDD, and highest in the hot-dry climate scenarios with uneven-aged management, more wind, and lower GDD.

3.2. Which management strategies are most effective at achieving objectives?

Overall, uneven-aged management was the most effective management strategy across all climate futures for producing the highest benefits across all objectives but it performed poorly in situations where management objectives included maximization of timber yields. Specifically, under the historical climate, harvesting more biomass (i.e. business-as-usual (BAU) plus 20 % and even-aged scenarios) than the current harvesting regimes (BAU) provided lower benefits of aboveground C storage, lower C in culturally-important species, and greater harvested C, but similar soil C and diversity (Fig. 4). Age diversity was also lower in scenarios with more harvesting, likely due to the harvesting of older stands. Conversely, harvesting less biomass (i.e. BAU minus 20 % and uneven-aged scenarios) promoted greater benefits of C storage of aboveground biomass, C storage by culturally-important species, and higher age diversity. Uneven-aged harvest scenarios increased the benefits of aboveground C (+36 %), C storage by culturally-important species (+36 %), and age complexity (+62 %) more than the other harvest scenarios, but caused a dramatic reduction in harvest C (−77 %), despite constant area harvested. Harvesting less biomass (BAU minus 20 %) caused only a 47 % reduction in harvesting benefits, but it was not as successful as uneven-aged management at promoting aboveground C (+22 %), C storage by culturally-important species (+16 %) and age complexity (+27 %). Adjusting BAU practices up or down by 20 % resulted in disproportionate effects. For example, BAU plus 20 % caused a 36 % increase in the benefits of harvested C compared to BAU, but BAU minus 20 % caused a 46 % decrease.

3.3. Does climate change make it universally more challenging to achieve objectives?

Under historical climate, increasing the BAU harvesting strategy by 20 % and using even-aged harvest treatments resulted in increased harvestable timber by 36 % and 24 % (Fig. 4), but climate change reduced this yield to 30 % and 19 %. Management played a larger role than climate in influencing aboveground C and cultural C (Fig. 4), but climate change made it more challenging to store C in soils and management was unable to compensate for the effect. Climate change also made it far more challenging to promote species diversity, reducing the benefits of diversity by 54 % compared to historical climate. On the other hand, climate change made it easier to promote age diversity. For example, uneven-aged management increased the benefits of age diversity by 62 % under historical climate and by 120 % under climate change.

The size and direction of the effects of climate change on ecosystem benefits was highly dependent on the climate scenario (Fig. 5). The less warming scenario tended to promote aboveground and soil C, whereas the moderate warming scenarios tended to reduce soil C but had no effect on aboveground C. The benefits of species diversity were reduced under all climate scenarios, though the magnitude varied, ranging from 47 % in the less warming scenario to 67 % in the high warming and drier scenario. Climate change tended to promote age diversity, with drier scenarios having lower diversity than scenarios with higher precipitation except under the high warming scenarios.

3.4. Which management strategies require the least tradeoffs between objectives across all climate futures?

We also calculated tradeoffs between each pair of objectives to quantify the extent to which coupled benefits are optimized, where higher values are indicative of greater tradeoffs between objectives. Tradeoffs were 13–37 % higher for uneven-aged management than in the other management scenarios under climate change (Fig. 6). This was a result of high bivariate tradeoffs for combinations of objectives that involved harvested wood C, although moderately high tradeoffs for other objectives were also observed when balancing C storage in culturally-important species and species diversity, and between species diversity and aboveground C. In scenarios with more harvesting (BAU

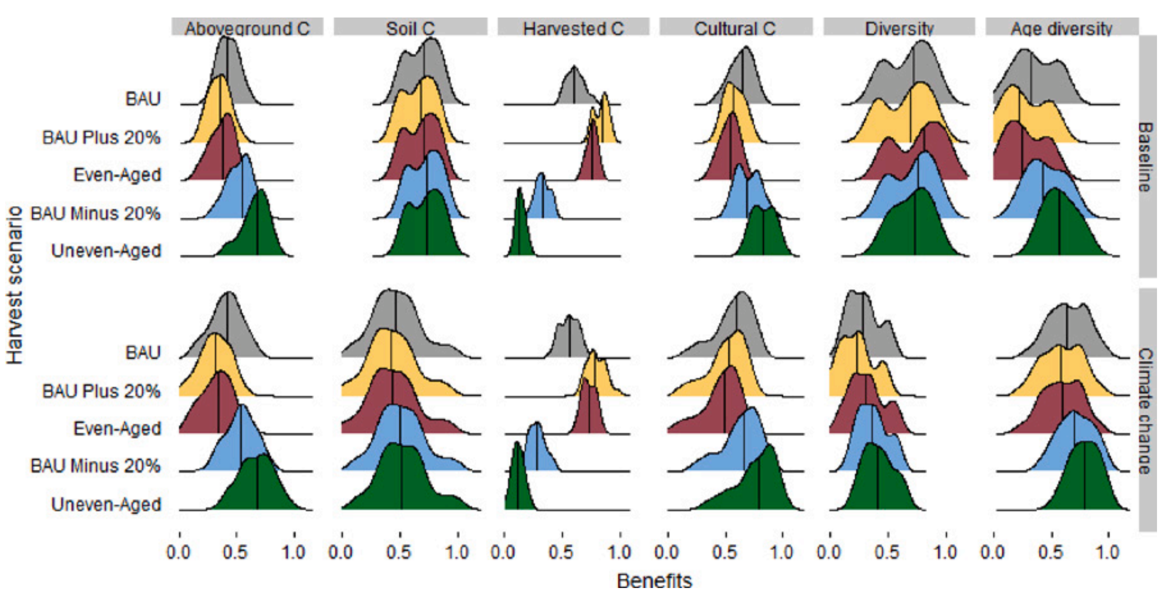

Fig. 4. Density plots of benefits for six objectives (aboveground carbon, soil C, harvested C, C stored in species of particular importance to the Menominee, Shannon's index of tree diversity, and tree age diversity) under five harvesting scenarios (BAU, business as usual; 20 % more harvested area, even-aged harvesting, 20 % less area harvested, and uneven-aged harvesting) under historical climate and climate change (mean of all the five climate change scenarios) at 2050.

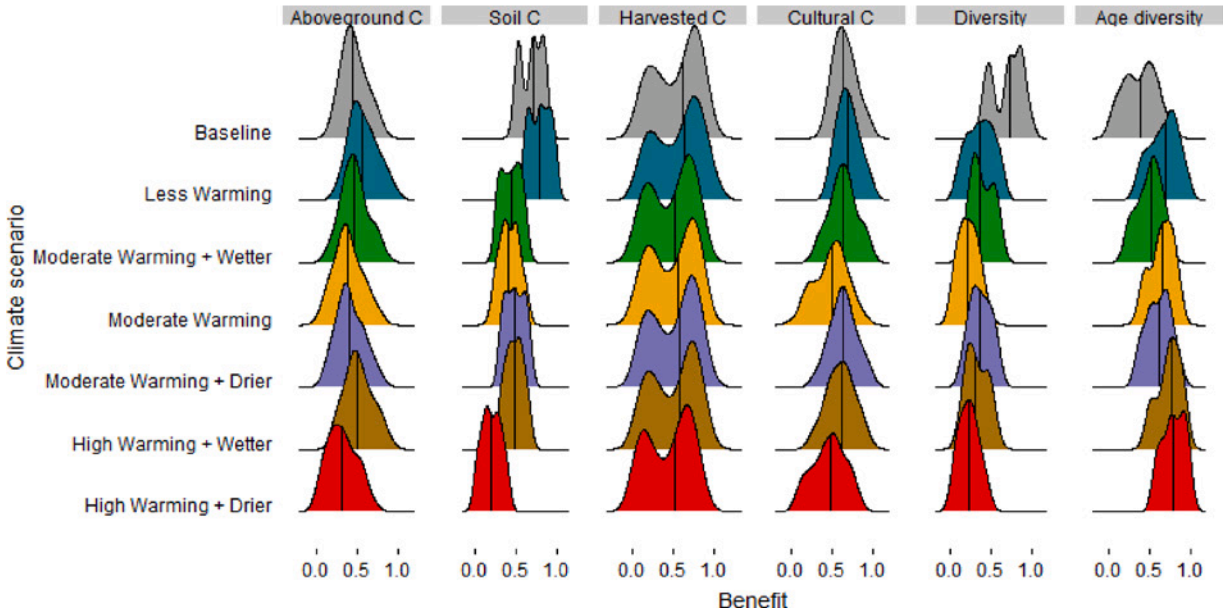

Fig. 5. Density plots of benefits for six objectives (aboveground carbon, soil C, harvested C, C stored in species of particular importance to the Menominee, Shannon's index of tree diversity, and tree age diversity) under each of the seven climate scenarios. These results include data from all the harvesting scenarios.

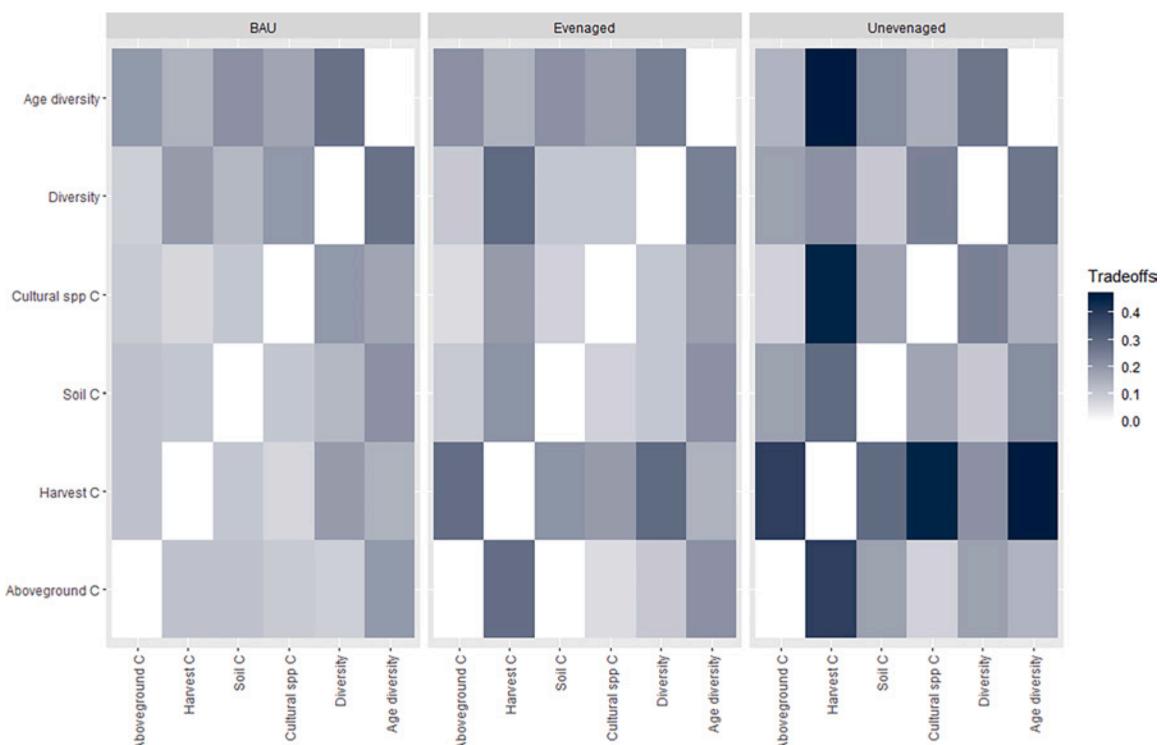

Fig. 6. Tradeoffs for all combinations of the six objectives (aboveground carbon, soil C, harvested C, C stored in species of particular importance to the Menominee, Shannon's index of tree diversity, and tree age diversity) under three harvesting scenarios (BAU, business as usual; even-aged harvesting, and uneven-aged harvesting). These results include output across all the climate change simulations. Results for all five harvesting scenarios are in Supplemental Figure 2S; results for each climate scenario are in Supplementary Figure 3S.

plus 20 % and even-aged), it was difficult to satisfy both the harvested carbon and aboveground C storage objectives simultaneously, and high tradeoffs were also noted between harvested C and species diversity objectives. Surprisingly, it was the business-as-usual scenario that produced the least amount of tradeoffs across all the objectives (BAU < BAU minus 20 % < Even-aged < BAU plus 20 % < Uneven-aged), even though it did not achieve the highest benefits for any individual management objective (Fig. 4).

We also expected low tradeoffs between species diversity and age diversity except in the even-aged harvest scenario, but we found relatively high tradeoffs between these objectives for all harvest scenarios.

3.5. What are the greatest sources of uncertainty in the benefits and tradeoffs?

Across the four different model scenario classes (harvest, climate, wind, GDDs), climate caused the highest uncertainty, quantified as the total variance in ecosystem benefits (Fig. 7). Harvesting was also an important source of uncertainty in the benefits of aboveground C and species diversity. Parameter uncertainty related to the seasonal timing of regeneration was a large source of uncertainty in harvested C, C in culturally- important species, and age diversity. Wind tended to be a smaller source of uncertainty than the other factors we considered.

The greatest source of uncertainty in tradeoffs, quantified as the total variance in ecosystem tradeoffs, was harvest (Fig. 8), except when promoting soil C or diversity was one of the objectives. Climate was the main source of uncertainty for tradeoffs involving soil C. Varying the amount of wind on the landscape generated the highest uncertainty in age diversity, which is not surprising given windstorms target older cohorts.

4. Discussion

Previous studies have highlighted the potential costs to forest structural and compositional diversity that may stem from a singular focus on harvesting or C storage (Burton et al., 2013; D'Amato et al., 2011) or discounting the relative importance of climate change as a driver of forest change (D'Amato et al., 2011; Ryan et al., 2010). Here, using state-of-the-art, high performance computing with a spatially explicit forest landscape simulation model, we were able to explore this decision space more comprehensively and robustly. Simulation modeling combined with multi-objective analysis can provide opportunities to objectively evaluate a larger suite of ecosystem objectives under climate change. In our study, uneven-aged management was the most effective management strategy to achieve many of our pre-defined management objectives, but it also required the largest amount of multi-objective tradeoffs. The inability of uneven-aged management to produce sizeable quantities of wood fiber meant that it did not perform well across all objectives, though it performed well in terms of storing C aboveground and in culturally important tree species and promoting age diversity.

4.1. Comparing the benefits and tradeoffs of different forest management strategies

When comparing tradeoffs and co-benefits across individual objectives, our results are consistent with those from temperate and boreal forests elsewhere. For example, tradeoffs between timber volume and forest C in stand-scale simulations from the northeastern United States were most pronounced for management approaches at either end of the harvest intensity spectrum (Carpentier et al., 2017). In Finnish boreal forests, landscape management strategies that maximized harvest volumes or revenues were inconsistent with achieving substantial forest ecosystem C storage (Eyvindson et al., 2018; Triviño et al., 2017). Schwenk et al. (2012) enumerated similar trade-offs between total C storage (i.e., forest ecosystem C plus C stored harvested wood products) and timber volume in Vermont, even after accounting for the contribution of the wood product pool to the climate mitigation potential of forests. These studies examined tradeoffs between timber production and C storage for a predefined set of operational silvicultural or landscape-scale management strategies. Simulation modeling using high performance computing, as used in our study, can be used to not only construct the envelope of joint production possibilities for timber and C, but also to examine novel management strategies along this production frontier that optimize a suite of ecosystem services (Ager et al., 2016; Kline et al., 2016; McCarney et al., 2008) under a range of climate change scenarios.

Although the BAU harvest scenario— which reflects the current harvesting practices in the Lakewood district— did not achieve the highest benefits for any individual management objectives in our simulations, this scenario minimized multi-objective tradeoffs when viewed in aggregate. Given the different stand-scale multi-objective tradeoffs associated with different silvicultural systems, management strategies that combine these various silvicultural systems may be able to balance seemingly competing objectives at large spatial scales (Povak et al., 2022; Schwenk et al., 2012). The results from our simulations are

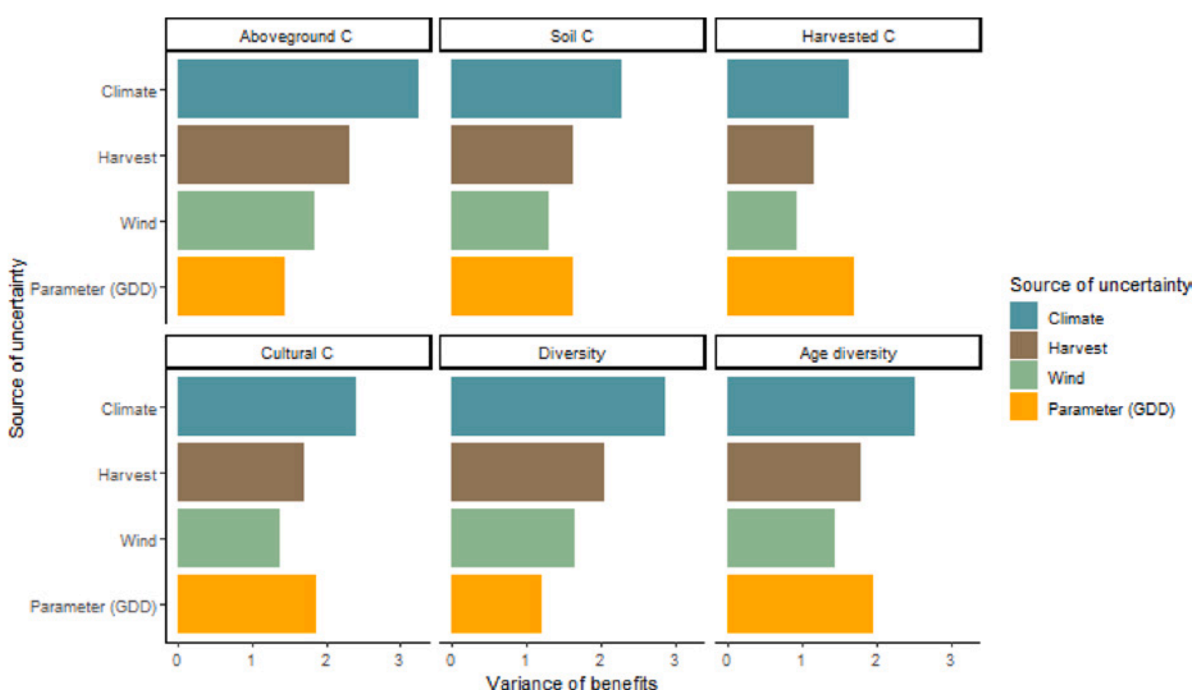

Fig. 7. Climate was the largest source of model uncertainty, quantified as the total variance in ecosystem benefits. Parameter uncertainty, that affected the seasonal timing of regeneration, was the greatest source of uncertainty in harvested carbon.

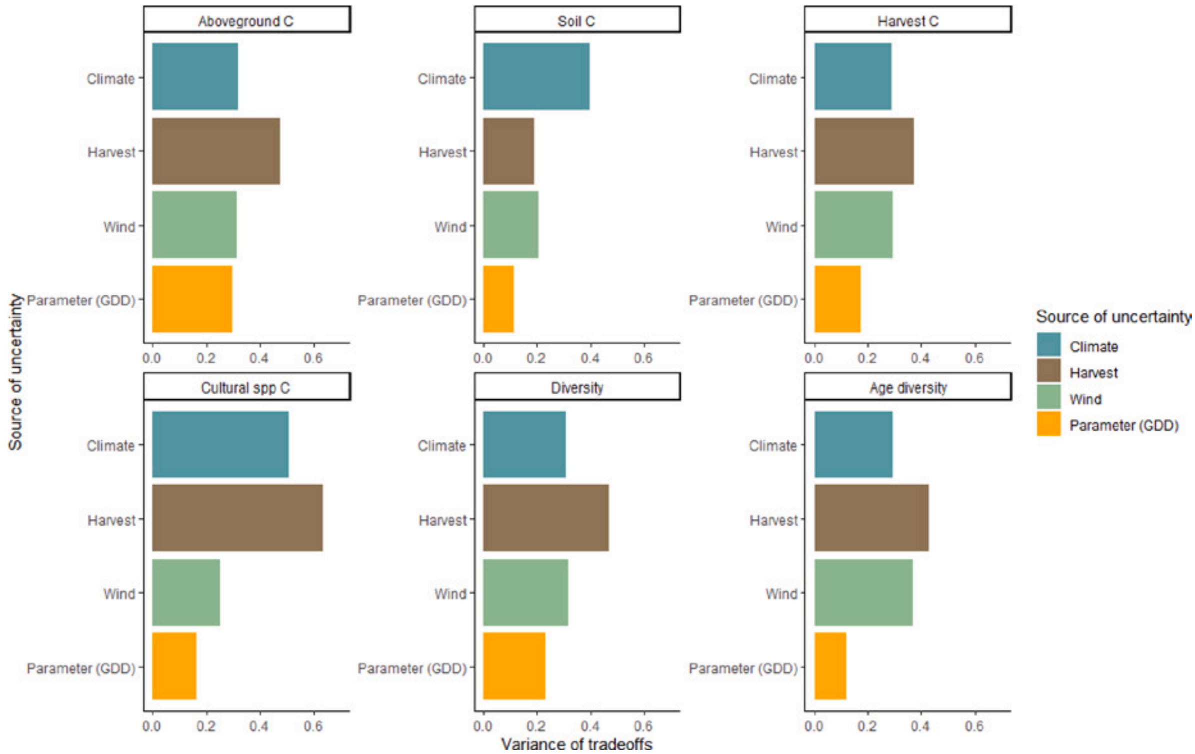

Fig. 8. Harvest was the largest source of model uncertainty in tradeoffs, except for soil C. Climate uncertainty was the greatest source of uncertainty in soil carbon.

consistent with these proposals. Scenarios that uniformly employed a single prescription achieved high benefits for certain objectives but low benefits for others, and frequently produced relatively high tradeoffs. By contrast, multi-objective tradeoffs for the BAU scenario were consistently low to moderate in relation to alternative harvest scenarios. While it is unlikely that tradeoff optimization has explicitly guided the management regime on our study landscape, matching management interventions to stand and site conditions to achieve landowner goals is fundamental to silviculture (Ashton and Kelty, 2018). A wide variety of stand structures and species compositions exist on the current study landscape, and silvicultural systems in these stands vary accordingly (reflected in the treatments modeled in our BAU scenario), from clear-cut systems in shade-intolerant jack pine stands, to group selection in shade-tolerant spruce-fir stands. Similarly, management objectives range from timber production to promoting the growth of culturally-important species, and this variety encourages the use of practices from across the harvest intensity spectrum. In this sense, our BAU scenario represents a variety of different stand management practices that, at landscape scale, produce the range of benefits desired by regional landowners, reducing landscape-scale trade-offs. In the future, as the climate changes, altering the proportional allocation of silvicultural treatments across the landscape, ideally with site-level geographic targeting, may provide a simple means of maintaining aggregate benefits under current landowner goals or modifying benefit provision to suit emerging landowner priorities (Fürstenau et al., 2007; Phelps et al., 2012).

4.2. Potential for climate change to limit the ability of managers to achieve their management goals

Harvesting provides an important lever for forest managers to help reach their management goals, but climate change can act as a leverage constraint that makes it challenging to achieve management outcomes while concomitantly introducing uncertainty. In our study, climate change made it more difficult to store C in soils and management was unable to regain these lost benefits, despite testing a wide range of options. Forest soils are an important component of the total ecosystem C storage in the Upper Midwest (Smith et al., 2019), and reductions in the size of this reservoir amount to a sizable net C loss through temperature-enhanced soil respiration (Bond-Lamberty and Thomson, 2010; Carey et al., 2016). If only minimal warming occurs over the next fifty years (i.e. less warming scenario), soil C may remain constant but soil C will likely decline under moderate or high warming scenarios with little ability of management to abate the declines. Climate change also reduced harvested C and C stored in culturally-important species, however, uneven-aged management was able to at least partially compensate for this effect. On aggregate, our results suggest that maintaining total forest sector C stocks, from vegetation to soils and wood products, is likely to become an increasingly challenging management objective under extreme climate change.

Climate warming had a pronounced effect on species and age diversity metrics; our simulations suggest that climate warming could lead to an aggregate reduction in compositional diversity, which is consistent with expectations for this landscape in our model configuration. Quaking aspen (*Populus tremuloidies*), balsam fir (*Abies balsamea*), black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) are projected to experience reduced habitat suitability under extreme climate warming, given the study landscape is proximal to their existing southern range margin (Janowiak et al., 2014; Peters et al., 2020). Our finding of reduced compositional diversity is consistent with the results of recent estimates for a similar northern Wisconsin landscape by Gustafson et al. (2020). In this study, heat stress in the more cold-tolerant species was identified as a factor in the observed decline of species at their southern range limits. Northward movement of species with existing distributions to the south of our study region, naturally or via management intervention (Duveneck et al., 2014; Janowiak et al., 2014; Swanston et al., 2016), may help compensate for reduced competitiveness of existing species, but we did not incorporate this potential response. Our results may therefore represent a relatively pessimistic assessment of future changes in species composition. However, there remain significant concerns over the ability of species' ranges to keep pace with changes in climate (e.g., Rogers et al., 2017; Sittaro et al., 2017) and other stressors like emerald ash borer (Olson et al., 2021), suggesting that a decline in compositional diversity in our study landscape is not unrealistic.

Our simulations also suggest that climate warming could lead to an increase in age-class diversity which is somewhat counterintuitive. Increased patch-scale age-class diversity under climate change in our model is counter to hypothesized mortality trends among young and old trees. The increase in age-class diversity implies a more even distribution across age classes. However, major challenges to seedling establishment and growth under warmer climates (with and without reductions in precipitation) have been identified in studies from across North America (e.g., Rother et al., 2015; Ibáñez et al., 2017; Boucher et al., 2020), and while these effects will not apply evenly across species (Fisichelli et al., 2014), the overall expectation is of negative pressures to seedlings. Even though mature trees are less vulnerable to these climate pressures (Gustafson et al., 2020; Mathys et al., 2018), increased mortality risks among the oldest age may be possible as the climate changes (Allen et al., 2010; McDowell et al., 2020; van Mantgem et al., 2009). Projected reductions in age-class diversity under extreme warming were reported by Gustafson et al. (2020), but are counter to the general direction of change visible in our model outputs, indicating a need for further inquiry. Our simulations did not include output maps of cohort ages, but future studies might benefit from analyzing shifts in the age distribution under climate change.

4.3. Uncertainty analysis

Perhaps unsurprisingly, climate change was the greatest overall source of uncertainty in our objectives, except for harvested C. Wind disturbance had a much smaller effect on overall uncertainty in benefits than expected. Wind is a major natural disturbance in forests of the Upper Midwest (Frelich, 2002; White and Host, 2008), and stochasticity in wind disturbance creates variability within individual model simulations for a given wind intensity (Scheller et al., 2011). Given that our simulations explored increases and decreases of 20 % wind disturbance area, compared to the existing wind regime, our results suggest that the area disturbed by winds of sufficient intensity to cause major disruption in successional pathways and C storage is minor compared to climate change. Parameter uncertainty was a large source of uncertainty in harvested C, reflecting the critical role of regeneration in providing a long-term supply of aboveground C. Harvesting was the largest source of uncertainty in tradeoffs, except when it came to soil C. Tradeoff analysis is highly dependent on the study location, scenarios, and other critical drivers are, highlighting the challenges of determining the relative importance of different drivers of uncertainty in complex models used in multi-objective decision-making.

5. Conclusions

Our study suggests that in this northcentral Wisconsin study landscape, uneven-aged management could provide higher benefits across a range of different ecosystem functions than other landscape-scale harvest scenarios, but may also entail greater tradeoffs when timber harvesting is an important forest management objective. Adopting uneven-aged management as the primary management tool might help maintain high forest C stores, but it would potentially compromise the ability to simultaneously produce significant quantities of wood fiber in this region. Current harvesting practices, reflected in our business-as-usual harvest scenario, produced the lowest amount of tradeoffs, providing support for matching management interventions to stand and site conditions and using a diverse portfolio of silvicultural treatments across the landscape in order to achieve landowner goals. Climate change may shrink the operating space for managers seeking to optimize benefits and minimize tradeoffs, and our work highlights the need for novel silvicultural approaches for managing with and adapting to uncertainty.

CRediT authorship contribution statement

Melissa S. Lucash: Conceptualization, Investigation, Formal analysis, Data curation, Software, Visualization, Writing – original draft, Funding acquisition. **Neil G. Williams:** Conceptualization, Investigation, Writing – original draft. **Vivek Srikrishnan:** Conceptualization, Investigation, Software. **Klaus Keller:** Conceptualization, Writing – review & editing, Funding acquisition. **Robert M. Scheller:** Writing – review & editing, Funding acquisition. **Casey Hegelson:** Conceptualization, Writing – review & editing. **Robert E. Nicholas:** Conceptualization, Software, Visualization, Writing – review & editing, Funding acquisition. **Erica A.H. Smithwick:** Conceptualization, Project administration, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

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

Data availability

The data that can be used to replicate the modeling results of this study are openly available on GitHub at: Model code to run LANDIS-II on the Penn State Roar cluster is openly available here: https://github.com/viff-cnh/.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2023.100460.

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