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Quantifying Nature-based Climate Solutions

Insights Into Nature-Based Climate Solutions: Managing Forests for Climate Resilience and Carbon Stability

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Key Points:

- Forest structure is primarily shaped by management, but interactions with regional climate change produce divergent structures over time
- Management can increase forest stability and minimize the release of stored carbon by reducing mortality in the face of climate change
- Management-induced changes in resilience are regionally dependent

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Successful implementation of forest management as a nature-based climate solution is dependent on the durability of management-induced changes in forest carbon storage and sequestration. As forests face unprecedented stability risks in the face of ongoing climate change, much remains unknown regarding how management will impact forest stability, or how interactions with climate might shift the response of forests to management across spatiotemporal scales. Here, we used a process-based model to simulate multidecadal projections of forest dynamics in response to changes in management and climate. Simulations were conducted across gradients in forest type, edaphic factors, and management intensity under two alternate radiative forcing scenarios (RCP4.5 and RCP8.5). This allowed for the quantification of forest stability shifts in response to climate change, and the role of management in modulating that response, where ecosystem stability is characterized as the resilience and temporal stability of net primary production, aboveground biomass, and soil carbon. Our results indicate that forest structure is primarily shaped by management, but the same management strategy often produced divergent structures over time, due to interactions with regional climate change. We found that management can be used to increase stability and minimize the release of stored carbon by reducing mortality, but also highlight the regional dependency of management-induced changes in resilience to climate change.

Plain Language Summary Successfully using forest management to help mitigate climate change depends on how well management can keep forests storing and absorbing carbon dioxide over time. As climate change continues, forests are facing new and serious risks, and we do not fully understand how management efforts will affect their stability. It is also unclear how climate changes might alter the way forests respond to management. In this study, we used a computer model to predict how forests might change over several decades due to different management practices and climate conditions. We looked at various forest types and levels of management intensity under two possible climate scenarios (moderate and high levels of greenhouse gas emissions). We measured stability in terms of how resilient forests are and how stable their growth, biomass, and soil carbon levels remain over time. The results showed that management practices have a significant impact on forest structure, but that the same management approach can lead to different outcomes depending on regional climate changes. We also found that management can improve forest stability and reduce carbon loss by lowering tree mortality rates. However, the effectiveness of these strategies heavily depends on the specific regional climate conditions.

1. Introduction

Emission reductions alone are insufficient to avoid the most catastrophic effects of climate change (Canadell & Schulze, 2014; National Academies of Sciences, Engineering, and Medicine, 2019; Rockström et al., 2021). Therefore, the active removal of atmospheric CO_2 must also be a core component of any feasible climate mitigation strategy (IPCC, 2022; Smith et al., 2016). Many proposed approaches to climate change mitigation require significant technological advances or are still largely experimental (Fuss et al., 2014). Nature-based climate solutions (NbCS), which manipulate natural systems through management and design to increase carbon sequestration and decrease greenhouse gas emissions (Novick et al., 2022), have emerged as prospective solutions

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that are less reliant on emergent technology. NbCS have the potential to sequester up to 1.2 Pg CO2 *e* year^{-1} in the United States (U.S.), which is approximately 21% of net annual emissions (Fargione et al., 2018), while also supporting a range of environmental and social cobenefits and potentially increasing resilience to future climate change impacts (Becknell et al., 2015; Fargione et al., 2018; Novick et al., 2022).

Successful implementation of forest management as a NbCS is dependent on the durability of management-induced changes in forest carbon storage and sequestration (Anderegg, Chegwidden, et al., 2022; Canadell & Raupach, 2008; Novick et al., 2022). However, recent evidence indicates that forest carbon sinks are becoming more vulnerable in response to the increased variability and magnitude of extremes in climate drivers (Forzieri et al., 2022; McDowell et al., 2020; Wu et al., 2023). Rapidly changing environmental conditions have the potential to decrease forest stability (Bauman et al., 2022; Reich et al., 2022); the resistance to changes in forest function or composition in response to disturbance, or the rate, variability, and extent of the return to predisturbance function or composition (i.e., resilience) (Hillebrand et al., 2018; Holling, 1973; Mathes et al., 2021; Tilman et al., 2006). As forests become less stable, the likelihood of large-scale mortality in response to climate-driven disturbances increases (Bauman et al., 2022; Forzieri et al., 2022; Reich et al., 2022), meaning that a significant portion of stored carbon could be released, potentially nullifying mitigation efforts (Anderegg, Chegwidden, et al., 2022; Reichstein et al., 2013). For example, Running (2008) estimated that Hurricane Katrina killed approximately 320 million trees, turning the Southeastern (SE) U.S. into a net carbon source that offset the entire annual U.S. terrestrial carbon sink in 2005.

Forest structure plays a critical role in determining the response of forests to climate stressors (Amiro et al., 2010; Anderegg, Chegwidden, et al., 2022). Variations in forest structure such as tree density, species composition, and tree size and age distributions influence forest stability by shaping resource availability and carbon dynamics (Anderson-Teixeira et al., 2013; Gough et al., 2019; Matheny et al., 2014), and targeted management has the potential to promote forest stability through structural manipulations that mitigate disturbance risk. For example, fuels reduction management (including thinning and prescribed fire) is frequently used to reduce the risk of severe fire and associated mortality (Hurteau et al., 2014), and a study by Brice et al. (2020) showed that moderate reductions in stand basal area reduced turnover and convergence times associated with forest transition, accelerating climate-driven biome shifts. However, fewer studies have examined the ability of management to moderate forest responses to climate change as a press disturbance across multidecadal timescales, while also accounting for climate feedback, despite the necessity to ensure that forest management NbCS are robust and scalable. Additionally, the evaluation of forest management as a NbCS has primarily focused on extended rotations as a management strategy (Fargione et al., 2018; Kaarakka et al., 2021), but other commonly applied silvicultural practices such as thinning (either of the understory or large tree removal) and selective harvest could enhance forest carbon sequestration and stability. Addressing this knowledge gap requires models that include climate sensitivity in forest dynamics projections, which current NbCS assessment tools, such as the Forest Vegetation Simulator (Dixon, 2002), do not support. Recent proposals on NbCS scientific priorities (Anderegg, Trugman, et al., 2022) underscored the need to integrate demographic models incorporating plant physiology, ecological dynamics, and climate sensitivity in the assessment process to ensure that NbCS are rooted in rigorous scientific understanding and emphasize that we must account for how climate feedback could alter carbon dynamics and disturbance responses (Novick et al., 2024).

Here, we used a process-based vegetation demography model to simulate multidecadal projections of forest dynamics in response to changes in management and climate in two regions: the Great Lakes (GL) and the SE U.S. Simulations span from 2006 to 2100 and are conducted under two Representative Concentration Pathways (RCP4.5 and RCP8.5) and three management strategies (even-age, high-intensity uneven-age, and low-intensity uneven-age) capturing a range of intensities in applied management practices. This enables the evaluation of forest stability shifts due to climate change, the role of management in modulating these shifts, and regional environmental variation. This study focused on the stability of existing carbon stored in aboveground biomass (AGB) and soils (referred to as compositional stability), as well as on the ability of the forest to sequester carbon (referred to as functional stability), represented by net primary productivity (NPP). Forest stability is characterized here as both resilience (speed of functional recovery following perturbation; Holling, 1973) and temporal stability (persistence of ecosystem function over time; Lehman & Tilman, 2000; Tilman et al., 2006). Several studies have adopted a multidimensional framework to evaluate stability in response to discrete disturbance events, such as stem girdling through the Forest Accelerated Succession Experiment (FASET; Gough et al., 2013; Mathes et al., 2021), or simulated mortality events across a range of severities (Dorheim et al., 2022). However, this study is among the first to evaluate the multidimensional stability response of forest carbon cycling to sustained management over multidecadal timescales and within the context of alternate climate change scenarios at the regional scale. Therefore, this work provides novel insights into how management impacts the structure and stability of forests across multidecadal timescales and how future climate change could potentially affect stability trajectories.

Specifically, we address the following questions: (a) How does management shape forest structure across multidecadal timescales, and do impacts differ depending on the emissions scenario? (b) How is the stability of forest carbon storage and sequestration affected by changes in forest structure, as shaped by management and climate, and are impacts regionally dependent? We hypothesize that forest structure is primarily shaped by management, and that the impact of management on structure will depend on management intensity. However, we also expect that structural responses to management will diverge regionally over time because of differences in regional climate change, particularly the significantly increased precipitation anticipated in the SE. We hypothesize that management is the most important factor shaping functional stability and that climate is the primary driver of compositional stability; however, regional interactions between management and climate change will alter stability outcomes over time and that more intensive management practices will decrease forest stability. Finally, we expect to see a positive correlation between forest stability and structural complexity, indicating that managing for enhanced structural complexity could promote forest stability in the face of ongoing climate change.

2. Methods

2.1. Site Description

National Ecological Observatory Network (NEON) core terrestrial sites in the GL and SE U.S. were selected for this study. National Ecological Observatory Network core terrestrial site locations were determined based on their representativeness of the U.S. ecological landscape along multiple axes of climate, edaphic, topographic, vegetation, wildlife, and management practices, using a statistical clustering algorithm (Schimel et al., 2007). The two regions chosen here represent a range of forest types and environmental conditions, and the use of NEON sites ensured ample data availability for model initialization. The University of Notre Dame Environmental Research Center (UNDE, 46.23°N, 89.54°W), located in Michigan's Upper Peninsula, represents the GL region. UNDE, a northern mesic forest site, features primarily second-growth forest with a history of clear-cutting in the early twentieth century (Mahon, 2003). UNDE experiences an average annual temperature of 4.5°C, 800 mm of average yearly precipitation, and notable winter snowfall. The soil, mainly Spodosols with some Histosols and Inceptisols, has sandy textures and originated in glaciofluvial deposits (Parsley, 2016). The area is characterized by forests, lakes, ponds, and bogs, with dominant tree species including red and sugar maple (*Acer rubrum* and *A. saccharum*, respectively), aspen (*Populus tremuloides* and *P. grandidentata*), and paper birch (*Betula papyrifera*) (Krauss, 2018).

The SE U.S. is represented by the Ordway-Swisher Biological Station (OSBS, 29.69°N, 81.99°W) and the Talladega National Forest (TALL, 32.95°N, 87.39°W) sites. Ordway-Swisher Biological Station, a longleaf pine site in North central Florida, experiences a humid subtropical climate with an average annual temperature of 21°C and an average precipitation rate of 1,300 mm per year. The soils are sandy, and impacted by silviculture (Prink & Figueroa, 2019). Dominant tree species include longleaf pine (*Pinus palustris*) and turkey oak (*Quercus laevis*) (Krauss, 2018), and the site is managed for recreation, habitat, and biodiversity, utilizing prescribed fires (Livingston, 2014). TALL, located in West Central Alabama, is predominantly longleaf and loblolly pine (*P. palustris* and *P. taeda*) with an understory of mixed oak and hardwoods (Hatcher, 2017). The site has a humid subtropical climate with an average annual temperature of 17°C and an average precipitation rate of 1,400 mm per year. Soils, developed from marine sediments, include sandy, loamy, and clayey types (Hatcher, 2017). TALL is managed for recreation, active logging, preservation, and habitat, involving regular midstory harvests and prescribed fires (Pasquill, 2006).

2.2. Ecological Modeling

2.2.1. Model Description

This study utilizes the Ecosystem Demography model version 2.1 (ED2; Moorcroft et al., 2001; Hurtt et al., 2002; Albani et al., 2006; Medvigy et al., 2009; Longo et al., 2019). ED2 is a vegetation dynamics model that simulates

10.1029/2024JG008391

population dynamics, demography, and community composition using a hierarchical structure. Rather than simulating individual trees, ED2 simulates cohorts–groups of trees with similar size and age characteristics–making it less computationally expensive than traditional forest gap models (Fisher & Koven, 2020) while maintaining its ability to represent complex ecological interactions. Cohorts in ED2 compete for available resources and are distributed across patches, each representing a spatially implicit microenvironment with a shared disturbance history (Longo et al., 2019). Patches are dynamic, meaning their fractional area changes in response to aging and disturbance. ED2's cohort-based approach facilitates harvest based on tree size and age, and its patch structure enables the evolution of forest structure, community composition, and microenvironment in response to disturbance. This makes ED2 uniquely well suited for exploring the impact of management and climate change on forest dynamics.

2.2.2. Model Simulations

Simulations used downscaled air temperature, precipitation, incoming shortwave and longwave radiation, specific humidity, air pressure, and wind speed from an ensemble of 10 Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) general circulation models (GCMs) (Table S1 in Supporting Information S1), for the period 2006–2100. A two-stage generalized additive modeling (GAM) approach (LeBauer et al., 2013; Simkins, 2017) downscaled meteorological data from daily to the subdaily resolution required by ED2 (see supplement S1 Section 1 for details). General circulation model output from two radiative forcing scenarios, RCP4.5 and RCP8.5, was used to explore forest responses to different climate futures. RCP4.5 represents a moderate emissions pathway involving significant mitigation, while RCP8.5 represents a business-as-usual scenario with unchecked emissions (van Vuuren et al., 2011). These scenarios cover a range of emissions trajectories, facilitating comparisons to other studies. Simulations were initialized with site-specific forest composition and structure data under a stable CO_2 concentration (380 ppm), corresponding to the atmospheric CO_2 concentration in 2006, when model simulations began. This avoided compounding effects of enhanced CO_2 on plant productivity (Bacastow & Keeling, 1973; Ciais et al., 2013; Walker et al., 2020), as potential CO_2 fertilization effects were not a focus of this study. ED2's sensitivity to CO_2 increases can result in unrealistic plant productivity responses and dominate prediction uncertainty over long timescales (De Kauwe et al., 2013, 2014; Rollinson et al., 2017; Walker et al., 2020; Zaehle et al., 2014).

Soil and vegetation data to initialize ED2 came from NEON plot and site-level observations. Soil characteristics, including texture, carbon and nitrogen content, bulk density, and microbial biomass, were obtained from megapit data products (DP1.00096.001, DP1.10104.001, and DP1.10098.001). Additional information on soil carbon (SOC) pool initialization is provided in the supplement. In situ measurements of tree density, height, diameter at breast height (DBH), and tree species at the plot scale were used to initialize vegetation. Tree species were converted to seven plant functional types (PFTs) recognizable by ED2, where PFTs are groups of species with similar physical, phylogenetic, and phenological characteristics (Wullschleger et al., 2014): a temperate C3 grass; southern pine; northern pine; late successional conifer; and early, mid, and late successional hardwood tree PFTs. All tree PFTs used default ED2 trait values; site-specific parameterization was not performed.

Management in simulations was represented as one of three types: even-aged, low-intensity uneven-aged, and high-intensity uneven-aged, reflecting a range of practices. Even-age management involves full or selective periodic timber harvest with minimal management between harvests, common among nonindustrial private forests (Carey, 2006). Due to model constraints, some age variability persists in even-age management because harvest is prescribed as a fraction of the total area each year, so rather than a “true” clear-cut, it is more akin to patch clear-cuts. Uneven-age management involves more frequent harvests targeting trees above a minimum marketable diameter. High-intensity uneven-aged forestry involves harvest practices that remove large fractional areas of trees with shorter return intervals than the low-intensity uneven-aged management scenario and incorporate understory thinning. Low-intensity uneven-aged management occurs on longer rotations and involves some understory thinning in the GL and regeneration support in the SE. A management-free control scenario provided a baseline for comparison. Management in ED2 is prescribed by altering the spatial extent of harvest and the size groups (tree diameter) and PFTs targeted for removal. Harvest rotations are implicitly represented by specifying a fractional area of trees to remove each year, calculated as 1/harvest rotation. Regional management parameters were derived from interviews with forestry experts in the regions of interest (von Hedemann and Schultz, 2021). For example, from these discussions, high-intensity uneven-age forestry in the GL is represented in ED2 with a 57-year rotation, which translates to a fractional harvest area of 1.8% per year, where trees with a

DBH above 26.67 cm have an 80% probability of harvest, and trees below have a 20% probability of harvest. To allow vegetation and climate forcing to equilibrate, simulation of management did not begin until 2020. Additional information regarding the derivation of management parameters is provided in the supplement, with detailed regional parameter values in Table S2 in Supporting Information S1.

Although ED2 can simulate natural disturbances, they were not explicitly represented to isolate the impact of management on functional and compositional responses to climate change. Simulations started from existing forest conditions rather than bare ground, so a prolonged spin-up period to build up ecosystem carbon pools was not necessary. Carbon fluxes simulated under the control scenario were compared against NEON-supported eddy covariance flux tower observations from UNDE, TALL, and OSBS (see supplement S1 Section 5).

2.3. Management and Climate Impacts on Forest Structure

Structural variables' output by ED2 were evaluated under each management and emissions scenario at the start and end of the century to determine average changes over time. Forest structure was characterized by nine variables: tree age (years), leaf area index (LAI), tree density (trees m^{-2}), the mean and standard deviation of tree DBH ($\overline{DBH}$ and σ_{DBH}, cm), crown area ($\overline{CA}$ and σ_{CA}, m), and tree height ($\overline{H}$ and σ_H, m). The standard deviation of tree diameter, crown area, and height represent variability in tree size and indicate canopy complexity, which has demonstrated links to forest productivity (Atkins et al., 2018, 2020; Gough et al., 2019; Hardiman et al., 2013; Murphy et al., 2022). All structural metrics natively exist at the cohort or patch scale in ED2 and were scaled to the site level using area-weighted averaging. Seedlings and saplings smaller than 12.7 cm in diameter and 1.37 m in height were excluded to remove bias from overrepresented seedlings, based on Forest Inventory and Analysis thresholds. One-way Kruskal-Wallis tests determined if forest structure differed significantly between management types within each region, and Dunn's post hoc test was applied to determine the significance for pairwise comparisons of individual structural variables. A Bonferroni adjustment was applied to p-values.

2.4. Forest Stability

This study evaluated the impact of forest management and climate change on forest stability, characterized as resilience and temporal stability. Resilience is the capacity of ecosystems to recover from perturbations (Holling, 1973), often represented as the rate of return to predisturbance function or composition (Hillebrand et al., 2018; Mathes et al., 2021), while temporal stability measures variability in function or composition relative to the mean state (Lehman & Tilman, 2000; Tilman et al., 2006). We assessed these impacts on three key variables: AGB, SOC, and net primary production (NPP). AGB and SOC represent existing carbon stores (compositional variables), and NPP represents ongoing carbon sequestration (functional variables). Additional information on representation of SOC in ED2 is provided in the supplement.

Monthly model output was the subset to the growing season, defined as periods with air temperatures above 5°C and gross primary productivity over 0.03 kg C m^{-2} $month^{-1}$ (Nelson et al., 2018). This definition of growing season was employed to accommodate regional differences in growing season length, and potential shifts in phenological timing that might occur due to climate change. Data were grouped by region, emissions scenario, management type, and GCM to calculate ratios between treatment and control values, and then averaged across GCMs to calculate annual resilience values. Temporal stability was determined over nonoverlapping 5-year intervals from the start of active management in 2020–2100. Data were organized into start (2020–2059) and end of century (2060–2100) bins and averaged to calculate net changes in forest structure, resilience, and temporal stability.

Stability was calculated using control scenarios under RCP4.5 and RCP8.5 and comparing them to simulations under management and climate treatments, where each treatment denotes a combination of the management type (even-age, low-intensity uneven-age, or high-intensity uneven-age forestry) or the management-free control scenario, and emissions scenario (RCP4.5 or RCP8.5), for a total of eight treatments applied in each region. Each treatment consists of 10 replicates; model output from each of the 10 GCMs represents a treatment replicate. Resilience was calculated following Hillebrand et al. (2018). Functional resilience is the regression slope of relative NPP over time (Equation 1), and compositional resilience, or the resilience of carbon stored as AGB and in soils, is the slope of similarity between control- and treatment group-stored carbon magnitude over time (Equation 2).

Equation 1 Mathematical representation of ecosystem functional resilience from Hillebrand et al. (2018). $F_{Perturbed}$ is the perturbed function value, $F_{Control}$ is the control function value, i is the intercept of the resilience regression line, t is time, and F_R is functional resilience.

$$ln\left(\frac{F_{Perturbed}}{F_{Control}}\right) = i + F_R * t \tag{1}$$

Equation 2 Mathematical representation of compositional resilience (Hillebrand et al., 2018), where compositional resilience refers to the resilience of stored carbon. $C_{Perturbed}$ is the perturbed compositional value, $C_{Control}$ is the control compositional value, i is the intercept of the resilience regression line, t is time, and C_R is compositional resilience.

$$sim\left(\frac{C_{Perturbed}}{C_{Control}}\right) = i + C_R * t \tag{2}$$

The similarity measure used in Equation 2 is Euclidean distance, the straight-line distance between two points in n-dimensional space, a measure frequently used for continuous numerical data. Similarity values between zero and one are possible, where values closer to one indicate a greater degree of similarity between two numbers. Resilience is a dimensionless quantity and can be positive, negative, or zero. Zero indicates no recovery, positive indicates rapid recovery, and negative indicates lower resilience than the control in response to forcing or perturbation (Hillebrand et al., 2018). Calculating resilience from the log ratio and similarity measures of perturbation to control values standardizes responses for comparison across variables with different units and magnitudes. Log-transformed resilience values were scaled by two orders of magnitude to facilitate interpretation of treatment differences. Scaling does not affect the relationships or significance of results but provides a more interpretable range of values. Temporal stability was calculated as the inverse of the coefficient of variation of the functional or compositional variable over a set timestep (Equation 3; Tilman et al., 2006; Lehman & Tilman, 2000; Tilman, 1999). This measure of temporal stability was used rather than the inverse of the standard deviation of resilience residuals (Hillebrand et al., 2018; Mathes et al., 2021), as it is more applicable when measuring stability over long time periods in the face of multiple fluctuating disturbances (Tilman et al., 2006), as opposed to capturing stability responses to single-pulse disturbance events (Hillebrand et al., 2018). Temporal stability is a dimensionless quantity that is inherently positive; larger values correspond to lower fluctuations around the mean trend in ecosystem function and composition over time. Temporal stabilities were log-transformed prior to analyses to facilitate comparison across variables with different units.

Equation 3 Mathematical representation of temporal stability, from Tilman et al. (2006). S_T is temporal stability, μ is the mean functional value over a set time period, and σ is the standard deviation of the functional value over the same time period. Temporal stability values are log-transformed to ensure normality and to facilitate comparison across variables with different units.

$$S_T = ln\left(\frac{\mu}{\sigma}\right) \tag{3}$$

A GAM, implemented using the *R* package *mgcv* version 1.8.42 (Wood, 2011) and fit using the restricted maximum likelihood method, assessed whether ecosystem stability was better predicted by management type or climate change scenario. Region was included as a predictor to control for inherent location-specific differences between the three study sites. This ensures that observed effects of management and climate change scenarios are not confounded by the substantial variability between site locations. Interactive effects between management type, region, and emissions scenario were included as predictors, with year included as a smoothed predictor using thin plate regression splines to account for temporal autocorrelation. Spearman correlation determined the directionality and strength of relationships between stability metrics and forest structure. Statistical significance of stability differences across management types, geographic regions, and emissions scenarios was tested using Tukey's Honestly Significant Difference (HSD) test with an alpha of 0.05. A Bonferroni adjustment was applied to p-values. All analyses were performed in *R* (R Core Team, 2021).

3. Results

3.1. Regional Climate, Productivity, and Stored Carbon Trends

Average monthly growing season precipitation and temperature increased from the start to the end of the century in both regions. Precipitation increased substantially in the SE, intensifying by 16%–20%, whereas increases in the GL were negligible (1%–2%). Precipitation increases were more pronounced under RCP4.5, and regional differences in precipitation were larger under the higher emissions scenario. Temperature increases were greatest under the high-emissions scenario (0.4°C–0.9°C increase under RCP4.5 compared to 0.6°C–1.9°C increase under RCP8.5), and regional differences became more pronounced over time. These simulated changes in precipitation and air temperature align with regional trends reported in the Fourth National Climate Assessment (USGCRP, 2018).

Productivity was highest in the GL, although regional differences narrowed over time (Figure S3 in Supporting Information S1), and NPP was higher on average under RCP8.5 than RCP4.5. For RCP4.5, productivity was highest under low-intensity even-age management in both regions (Figure S3 in Supporting Information S1). Productivity did not differ significantly by the management type under RCP8.5 in the GL, and NPP was highest under even-age and high-intensity uneven-age management in the SE. In addition to higher productivity, carbon stores were larger in the GL. Soil carbon stores were approximately twice as large in the GL (64.02–65.80 kg C m^{-2} under RCP4.5 and 59.95–62.85 kg C m^{-2} under RCP8.5), with the highest values observed under low-intensity uneven-age management, while in the SE, SOC averaged 31.24–32.65 kg C m^{-2} under RCP4.5 and 32.79–35.34 kg C m^{-2} under RCP8.5. The amount of carbon stored as AGB averaged 13.09–17.45 kg C m^{-2} under RCP4.5 and 13.55–17.76 13.09–17.45 kg C m^{-2} under RCP8.5 in the GL, with the highest values under low-intensity uneven-age management. In the SE, AGB averaged 10.55–12.72 kg C m^{-2} under RCP4.5 with the highest values under low-intensity uneven-age management, and 9.56–12.15 kg C m^{-2} under RCP8.5, with the highest values under even-age management.

3.2. Management and Climate Impacts on Forest Structure

Forest structure differed significantly between management types in the SE, but less so in the GL, where differences between the two intensity levels of uneven-age management scenarios were often not significant. Generally, structural differences were more pronounced between management types than between emissions scenarios, although emissions-related differences in mean tree height and size variability (σ_H, σ_{DBH}, and σ_{CA}) were notable. However, the impact of management strategies varied regionally, often producing divergent structural outcomes over time. Impacting forest structure, tree mortality rates increased by 70.25%–98.21% from the start to the end of the century, with the highest mortality rates observed under the control scenario. All active management strategies reduced tree mortality compared to the control. Even-age management had the lowest mortality rates in the GL, while high-intensity uneven-age forestry had the lowest mortality rates in the SE. In the GL, slightly higher mortality rates were associated with a more severe emissions scenario, but the opposite trend was observed in the SE.

In the absence of management, trees in the SE tended to have larger diameters, higher LAI, and greater size variability (σ_{DBH} and σ_H) than trees in the GL by the end of the century, while trees in the GL had higher average crown size and variability ($\overline{CA}$ and σ_{CA}) and were more densely populated; however, average tree age and height was similar between the two regions (Table S4 in Supporting Information S1). Tree age, size ($\overline{DBH}$ and $\overline{H}$), and variability in size (σ_{DBH} and σ_H) increased over time in both regions. LAI and variability in crown size (σ_{CA}) increased over time in the SE, but changes were minimal in the GL. Density decreased over time in the GL but exhibited minimal change over time in the SE. By the end of the century, active management resulted in younger trees with reduced size variability (σ_H and σ_{DBH}) than the control in both regions under RCP4.5 (Table S4 in Supporting Information S1). Even-age management decreased tree height and diameter relative to the control in both regions (Figure S1 in Supporting Information S1) but increased average crown size in the SE, and decreased variability in crown size in the GL but did not differ significantly from the control in the SE under RCP4.5. Even-age management resulted in the youngest average stands in the GL (Figure 1). Tree density and LAI did not differ significantly from the control scenario in either region under even-age management (Figure 1, Figure S2 in Supporting Information S1). Low-intensity uneven-age management decreased average crown size and

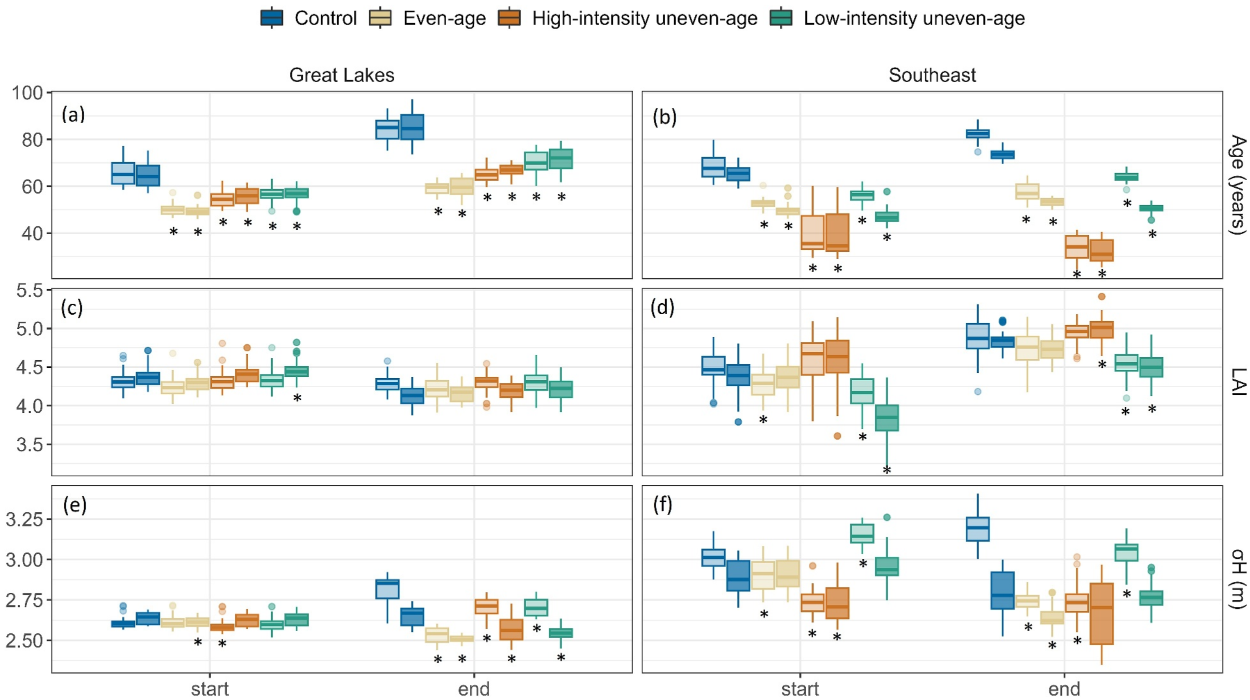

Figure 1. Average age, leaf area index (LAI), and standard deviation of tree height (σ_H) for the start and the end of the century. Columns are organized by geographic regions (a, c, e are GL and b, d, f are SE); color hue corresponds to the management type, and color tone corresponds to climate change scenario, where lighter tones represent RCP4.5 and darker tones represent RCP8.5. Within a region, emissions scenario, and century, "*" indicates whether distributions under a given management type differed significantly from the control scenario at an alpha level of $p < 0.05$.

variability relative to the control in both regions (Figures S1 and S2 in Supporting Information S1) and resulted in lower LAI and tree density in the SE and taller trees in the GL. Low-intensity uneven-age management did not significantly impact $\overline{DBH}$ in either region under RCP4.5, meaning tree $\overline{DBH}$ was comparable to the control (Figure S1 in Supporting Information S1). High-intensity uneven-age management decreased crown size and variability relative to the control in both regions and decreased tree size ($\overline{DBH}$ and $\overline{H}$) in the SE, but differences were not significant in the GL. LAI did not differ significantly from the control scenario in either region under high-intensity uneven-age management for RCP4.5 (Figure 1).

Structural variables representing tree height and variability in tree size (σ_H, σ_{DBH}, and σ_{CA}) were particularly sensitive to differences in climate by the end of the century (Table S4 in Supporting Information S1). Tree heights were significantly different by emissions scenario for all management types in the GL, and for high-intensity uneven-age forestry in the SE (Figure S1 in Supporting Information S1). Average tree height increased for all management types under RCP8.5 in the GL, and for high-intensity uneven-age forestry in the SE. However, height differences between emissions scenarios under active management were less pronounced than height differences between emissions scenarios for the management-free control in both regions, suggesting management effectively reduced the climate sensitivity of tree height to some degree. Variability in tree size (σ_H, σ_{DBH}, and σ_{CA}) was generally lower under RCP8.5 in both regions. Active management minimized the effect of emissions scenario on height variability relative to the control in both regions (Figure 1). Even-age management in the GL and high-intensity uneven-age management in the SE exhibited the lowest height variability climate sensitivity. Even-age and high-intensity uneven-age management minimized emissions-driven differences in σ_{DBH} relative to the control in the SE, but low-intensity uneven-age management increased the climate sensitivity of σ_{DBH}. High-intensity uneven-age management dampened the response of σ_{CA} to climate intensification in the GL, but even-age management was the most effective in the SE.

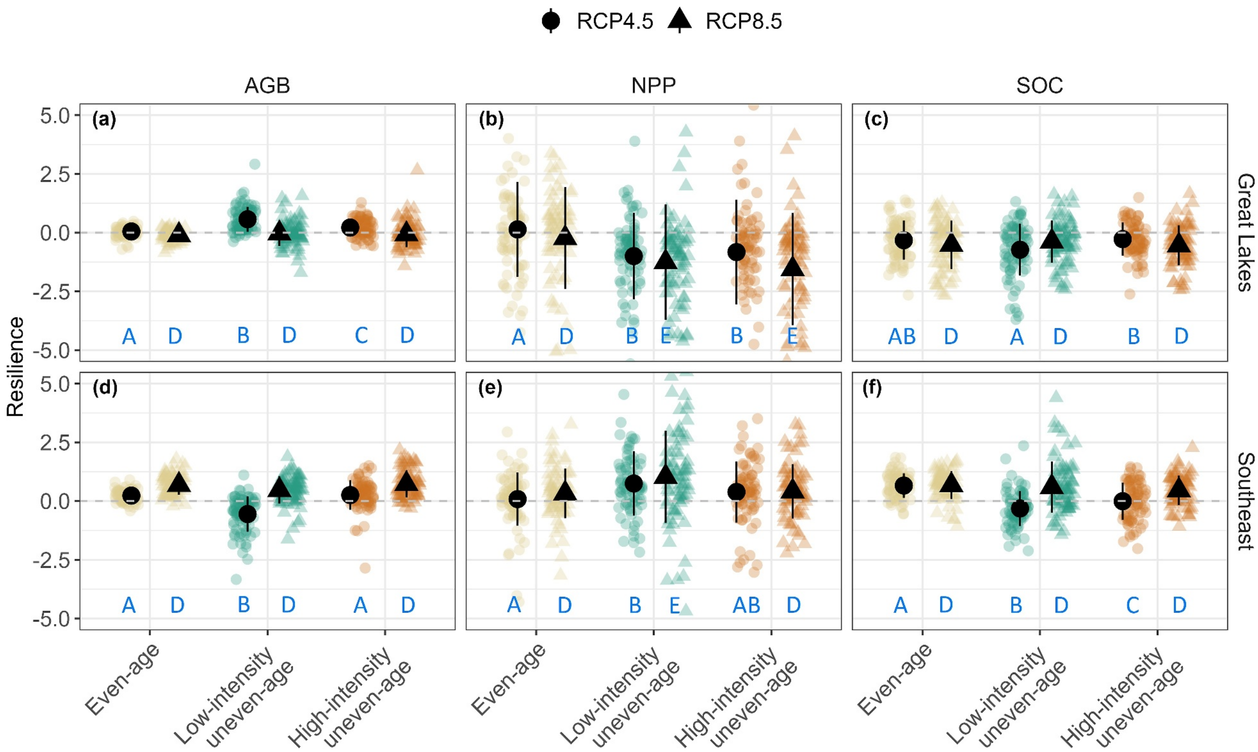

Figure 2. Mean annual aboveground biomass (AGB; panels a and d), net primary productivity (NPP; panels b and e), and soil carbon (SOC; panels c and f) resilience by management type and emissions (RCP) scenario. Individual points are annual averages, and point shapes correspond to emissions scenarios. Black points are overall group means from 2020–2100 (error bars denote $\pm 1\ \sigma$). For clarity, NPP resilience values >5 and <−5 are not shown here, but contributed to group means. Letters indicate statistically significant differences in resilience by the management type, evaluated within each region and emissions scenario. Groups sharing the same letter are not significantly different from each other, while groups with different letters are considered statistically significant at an alpha level of $p < 0.05$. Letters A, B, and C correspond to RCP4.5, and letters D, E, and F correspond to RCP8.5.

3.3. Management and Climate Impacts on Forest Stability

3.3.1. Resilience

Functional (NPP) resilience differed significantly between even-age and uneven-age management in the GL but did not differ within uneven-age management types (Figure 2). In the SE, NPP resilience differed significantly between even-age and low-intensity uneven-age management. The impact of specific management strategies on functional resilience was regionally dependent. For example, uneven-age management lowered functional resilience relative to the control in the GL but enhanced it in the SE (Figure 2). Even-age management had the best functional resilience outcomes in the GL, while low-intensity uneven-age forestry had the greatest positive impact in the SE (Table S5 in Supporting Information S1). Functional resilience decreased from the start to the end of the century in both regions and was higher on average in the SE (Table S5 in Supporting Information S1). Functional resilience did not differ significantly between emissions scenarios within management types.

The impact of individual management strategies on compositional resilience was also regionally dependent. In the SE, SOC compositional resilience differed significantly between all management types under RCP4.5, and AGB resilience under low-intensity uneven-age management differed significantly (Figure 2). In the GL, SOC resilience differed between the two uneven-age management strategies under RCP4.5, and differences in AGB resilience were significant for all management types under RCP4.5. However, under RCP8.5, differences in compositional resilience by the management type were not significant in either region (Figure 2). High-intensity uneven-age and even-age management had the greatest positive impact on compositional resilience in the SE, enhancing resilience relative to the control, but the magnitude of enhancement depended on the emissions scenario. In the GL, the resilience of stored carbon was typically lower under the higher emissions scenario, although the region experienced decreased compositional resilience and reductions in total AGB and SOC over time under both emissions scenarios (Figure S3 in Supporting Information S1). Conversely, in the SE, compositional

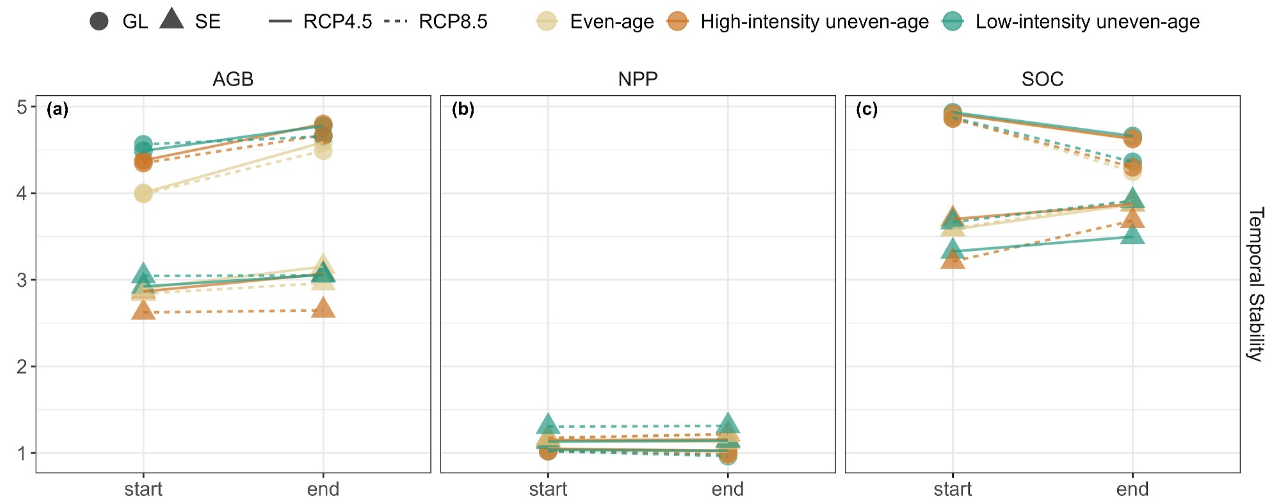

Figure 3. Average start and end of the century temporal stability by region (point shape), management type (color), and RCP scenario (line type) for (a) aboveground biomass (AGB), (b) net primary productivity (NPP), and (c) soil carbon (SOC).

resilience was higher on average under RCP8.5, with considerable increases in aboveground carbon stores over time.

3.3.2. Temporal Stability

The temporal stability of productivity was notably lower than that of stored carbon stocks due to the high interannual variability in NPP (Table S6 in Supporting Information S1). Regional differences in temporal stability were more pronounced for stored carbon stocks (AGB and SOC), compared to functional temporal stability (NPP, Figure 3). Compositional temporal stability was generally higher in the GL, although SOC temporal stability differences decreased over time as SOC declined steadily in the GL during the second half of the century. AGB temporal stability increased slightly from the first to the second half of the century in both regions, with differing trends in AGB magnitude. Overall, AGB decreased in the GL and increased in the SE, but both became less variable in time, resulting in increased temporal stability.

Differences in functional temporal stability between management types were insignificant, but significant differences were observed in compositional temporal stability between high-intensity uneven-age and even-age management, as well as between high- and low-intensity uneven-age management in the SE. AGB temporal stability was highest under low-intensity uneven-age and even-age management in the SE, while SOC temporal stability was highest under even-age management in the SE. Temporal stability differed significantly between emissions scenarios in both regions.

3.4. Predictors of Ecosystem Stability

The GAM predicting forest stability as a function of time, management type, emissions scenario, and region (including interactive effects) showed that after accounting for baseline differences across locations, the interaction term between management and the region was the primary driver of functional resilience ($\eta_P^2 = 0.04$) and compositional temporal stability ($\eta_P^2 = 0.02$) (Table 1), while the interaction term between emissions scenario and the region was the primary driver of compositional resilience ($\eta_P^2 = 0.06$) and functional temporal stability ($\eta_P^2 = 0.05$). The importance of the interaction terms relative to the driver strength of management or emissions scenario alone highlights that both management and emissions scenario have context-dependent influence, and that local site characteristics modulate how management and emissions scenario impact ecosystem stability. Management alone also had a significant impact on stability, but it depended on emissions scenario, and vice versa. Finally, our analysis revealed that management and emissions scenario interacted to alter stability outcomes for temporal stability and compositional resilience.

Table 1
Strength of Management Type, Emissions Scenario (RCP), and Region Group Membership as Predictors of Ecosystem Functional Stability

			Resilience			Temporal stability		
	Predictor	Df	SS	F-value	Partial $\eta 2$	SS	F-value	Partial $\eta 2$
Function	Region	1	397.40	121.55*	0.11	35.01	2054.08*	0.68
	RCP	1	4.10	1.26	0.00	0.40	23.66*	0.02
	Management	2	36.50	5.58*	0.01	0.26	7.77*	0.02
	Region:RCP	1	24.10	7.39*	0.01	0.90	52.97*	0.05
	Region:Management	2	135.60	20.74*	0.04	0.43	12.52*	0.03
	RCP:Management	2	5.90	0.91	0.00	0.52	15.36*	0.03
	Region:RCP:Management	2	0.50	0.07	0.00	0.44	13.01*	0.03
Composition	Region	1	121.50	229.02*	0.11	119.90	318.05*	0.14
	RCP	1	16.30	30.75*	0.02	5.10	13.64*	0.01
	Management	2	15.50	14.63*	0.02	7.10	9.36*	0.01
	Region:RCP	1	67.40	127.04*	0.06	2.80	7.48*	0.00
	Region:Management	2	28.70	27.01*	0.03	16.10	21.38*	0.02
	RCP:Management	2	13.90	13.08*	0.01	0.60	0.83	0.00
	Region:RCP:Management	2	9.30	8.79*	0.01	0.00	0.02	0.00

Note. *$p < 0.05$. "*" Symbols next to f-values denote statistical significance at an alpha value of 0.05, and ":" symbols between predictors indicate interaction effects between categorical factors. Df = degrees of freedom and SS = sum of squares.

3.5. Managing for Enhanced Resilience

Our analysis revealed that specific structural factors affect functional and compositional resilience. We found that targeted management activities could improve resilience (Figure S4 in Supporting Information S1), but their effectiveness was regionally dependent. In the SE, trees with greater variability in height were linked to higher functional resilience, while high LAI, tree density, and crown size were associated with reduced resilience. Conversely, in the GL, high LAI, tree density, and crown size were associated with higher NPP resilience, while an abundance of large, older trees was linked to lower resilience. AGB and SOC resilience had opposing relationships in the GL and SE, suggesting trade-offs when managing for compositional resilience. In the SE, higher LAI and larger, more variable crowns were linked to enhanced AGB and SOC resilience, respectively. In the GL, managing for older, taller trees with variable DBH enhanced AGB resilience, and increased stand density, and larger crowns resulted in higher SOC resilience (Figure S4 in Supporting Information S1).

4. Discussion

This study investigated the long-term impact of forest management and climate change on the structure and function of forests in two regions, the GL and the SE U.S., over a multidecadal time frame. Forest management was represented as one of three types: even-aged, low-intensity uneven-aged, and high-intensity uneven-aged management, which were defined by regionally specific model parameters. Alternate climate futures were represented with two representative concentration pathways, RCP4.5 and RCP8.5, using downscaled CMIP5 meteorological forcing data. We assessed the impact of management and climate change on forest structure compared to a control scenario without management intervention and evaluated the response of forest functional and compositional stability, measured as resilience and temporal stability. Finally, we analyzed the drivers of the observed changes in forest stability, and outlined potential management techniques that could enhance forest resilience in the two regions.

4.1. Management and Climate Impacts on Forest Structure

The first research objective was to examine the impact of varying levels of management intensity on forest structure across multidecadal timescales and explore whether the effects were regionally dependent or climate change scenario-specific. Nine variables, including LAI, density, age and size distributions of trees, and the structural complexity of forests, were used to represent forest structure. Tree height and size variability demonstrated strong climate sensitivity in both regions, but structural variables differed more between management types than between climate scenarios, consistent with recent work showing that anthropogenic disturbance is a stronger driver of compositional changes than climate at the century scale (Danneyrolles et al., 2019). A notable climate-driven mortality signal was observed in the GL, which saw amplified tree mortality for most management types under the higher emissions scenario.

The same management strategy often produced divergent structural outcomes over time when applied in different regions, likely due to interactions with regional environmental conditions and climate change. While management might be the primary factor shaping forest structure, climate shapes vegetation composition and functional diversity (Harrison et al., 2020; Kreft & Jetz, 2007) through temperature and moisture availability, which contribute to changes in structure as trees compete for available resources. For example, Ehbrecht et al. (2021) found that global variability in the structural complexity of undisturbed primary forests was largely determined by annual precipitation and precipitation seasonality, and Danneyrolles et al. (2019) drew connections to the implications of increased variability and magnitude of temperature and precipitation extremes under future radiative concentration pathways, showing that the probability of large compositional and structural changes in vegetation is greater under high-emission scenarios (RCP8.5). Within ED2, ecosystem structure evolves in response to tree growth, reproduction, mortality, disturbance, and aging (Longo et al., 2019), and functional diversity and its effects on competitive advantage are represented, meaning the influence of climate and interactions with management through shaping ecosystem structure can be captured.

The management-free control scenario in both regions featured large, tall, older trees with high AGB, consistent with studies on the effect of excluding management on carbon stocks (Andrews et al., 2018; Brice et al., 2020; Laflower et al., 2016). Among the management strategies, structural outcomes under even-age management differed the most, while the two uneven-age management strategies often had similar outcomes, especially in the GL. Even-age management led to dense stands of shorter and smaller trees with large crowns and low variability in diameter, which is consistent with recent studies evaluating global forest demographic responses to increased climate variability (McDowell et al., 2020; McIntyre et al., 2015). This compositional shift is likely more prominent under even-age management than under the control due to the periodic harvesting of large trees accelerating community transition. In the GL, even-age management resulted in stands of young trees with low average AGB, low structural complexity, and lower mortality. This suggests a simplification of canopy structure in response to intermittent management, which contrasts to work showing that small-scale intermittent disturbances often result in increased canopy complexity (Ehbrecht et al., 2017; Hardiman et al., 2013), for example, by creating gaps in the canopy that allow for light penetration and support understory development (Willim et al., 2019). However, this may be a consequence of the simulated disturbance having the same intensity and targeting the same PFTs and size classes for removal with each recurrence. Even-age management had similar but less pronounced effects on structural complexity in the SE, although variability in crown size increased, potentially due to the region experiencing less heat and water stress than the GL, both of which have been linked to crown dieback (Matusick et al., 2018).

Uneven-aged management is characterized by moderately tall trees with a higher LAI than the control in both regions. Structural differences between the two uneven-age management strategies were often not significant in the GL, although trees were taller and larger with lower densities under uneven-age management, and variability in height and DBH was greater. In the SE, high-intensity uneven-age management led to younger average ages, high variability in tree diameter, and low mortality, suggesting successful recruitment and survivorship. In contrast, low-intensity uneven-age management in the SE resulted in lower LAI but larger average diameters and greater structural complexity. In practice, extended rotations combined with thinning or regeneration support have been used to promote structural complexity and ecological dynamics that are more commonly observed in mature or old-growth forests (Kaarakka et al., 2021). These findings support the hypothesis that the response of forest structure to management depends on management intensity and severity and that structural responses to management will diverge regionally due to differences in regional climate change impacts.

Notably, mortality was highest under the control scenario in both regions and increased substantially by the end of the century. This suggests that management could buffer the acceleration of climate-driven mortality, although the extent to which this is observed depends on the management type and the region. Mortality in ED2 is determined by aging, carbon starvation, fire, and cold or frost events (Longo et al., 2019). Carbon starvation as a driver of mortality is density-dependent, meaning it occurs in response to trees actively competing for shared resources such as light and water. Therefore, the decreased rates of mortality observed under active management could potentially be attributed to intermittent harvest reducing competition for limited water resources, and the substantial increases in mortality over time under the control scenario indicate that these resources increase in scarcity under climate change. For example, in the SE, uneven-aged management- which periodically removes large-diameter trees- resulted in lower mortality rates compared to even-age management and the control. However, high-intensity uneven-age management, which also involved understory thinning, had the lowest mortality rates across all emissions scenarios.

4.2. Forest Stability

The second research objective was to determine how forest management alters ecosystem stability in the face of climate change and whether relationships are regionally dependent. We hypothesized that more intensive management practices would decrease forest stability but found that stability outcomes were largely regionally dependent. For example, in the SE, high-intensity uneven-age management enhanced functional (NPP) resilience relative to the control regardless of climate change scenario, but the same strategy had the opposite effect in the GL. The higher functional resilience in the SE could be partially attributed to regional climate differences. According to the physiological tolerance hypothesis, warmer and more humid climates support a broader range of plant functional strategies, leading to greater tolerance to climatic shifts like temperature, moisture, and light (Harrison et al., 2020). Additionally, the SE experienced increased water availability under both emissions scenarios, which has been linked to accelerated recovery rates after disturbance (Anderson-Teixeira et al., 2013).

Of the three management approaches, only even-age management positively impacted functional resilience in the GL. Notably, only even-age management reduced average tree height and size relative to the control in the GL, and larger trees have a greater risk of mortality under water stress (McIntyre et al., 2015; Nepstad et al., 2007) due to hydraulic failure and carbon starvation (McDowell & Allen, 2015; Sevanto et al., 2014). For example, Stovall et al. (2019) showed that tree height was the strongest predictor of mortality during drought conditions, with large trees dying at twice the rate of small trees, and mortality risk increasing nonlinearly with environmental stress. Although hydraulic failure is not explicitly represented in ED2, both the mortality rate and the growth rate depend on tree size and carbon balance. Management impacts on compositional resilience, or the resilience of carbon stored as AGB and in soils, were also regionally dependent, with significant differences observed between management types in the SE but not in the GL. Both high-intensity uneven-age and even-age management enhanced compositional resilience relative to the control in the SE, although their effectiveness differed depending on emissions scenario. The GL experienced lower compositional resilience under the high-emissions scenario than the SE, particularly in SOC stores, suggesting greater climate sensitivity. Temperatures increased slightly in the GL, which has been linked to accelerated decomposition of organic matter and carbon compounds in the soil (Natali et al., 2014; Schuur et al., 2015; Turetsky et al., 2020). However, the GL also became more water-limited during the growing season, likely reducing SOC resilience due to decreased organic inputs in dry conditions, as evidenced by the decrease in AGB. Temporal stability analysis revealed that regional differences were most pronounced for stored carbon stocks, with higher stability observed in the GL. However, this finding can be misleading, as the magnitude of carbon stored in AGB and soils decreased over time in the GL while also becoming less variable, resulting in higher compositional temporal stability than the SE, where the magnitude of carbon stores was more variable. The high temporal variability in the SE is likely related to increased variability in environmental conditions, particularly precipitation extremes.

We hypothesized that management is the most important factor shaping functional stability but found that while management is the most important driver of functional resilience, functional temporal stability was more closely linked to emissions scenario. This is likely due to the tight coupling between primary production and environmental drivers of photosynthesis that vary latitudinally and experience significant interannual fluctuations (Desai, 2010; Desai et al., 2022). However, management and interactions between climate change and management were still significant predictors of functional temporal stability, reflecting the influence of both micro- and macroenvironmental conditions on NPP. For example, temperature and vapor pressure deficit can vary across large scales because of climate change, but they can also vary at small scales due to differences in the horizontal and the vertical positioning of trees, abundance of canopy gaps, etc., which are directly impacted by management. Additionally, this finding could be partially attributed to the influence of management on successional dynamics across multidecadal timescales, capturing NPP responses to shifts in community composition and competition.

Compositional resilience was primarily shaped by regional scale climate, although interactions between emissions scenarios and management were also significant drivers. This finding is consistent with the work by Felipe-Lucia et al. (2018), which found that environmental factors followed by the combination of structural attributes and environmental factors were the strongest drivers of variability in SOC in temperate forests. This suggests that while focusing mitigation efforts on enhancing functional resilience might be the most impactful, the impact of proposed mitigation strategies on compositional resilience cannot be ignored when designing mitigation plans. Importantly, the dominance of management-region interaction terms and emissions scenario-region interaction terms over the importance of management or emissions scenario alone emphasizes that both management and emissions scenario have context-dependent influence, and that local site characteristics modulate how management and emissions scenario impact ecosystem stability. The positive effects of management on functional and compositional resilience were generally more pronounced in the SE, whereas management often reduced resilience relative to the control in the GL, particularly under the high-emissions scenario. This suggests that alternate management strategies beyond those evaluated here should be explored for the GL, along with associated climate sensitivities.

Additionally, targeting specific structural attributes through management could increase functional resilience in the face of ongoing climate change, but trade-offs often exist. For example, increasing functional resilience in the SE came at the expense of SOC resilience. We also showed that management approaches to bolstering resilience must be regionally specific, as a strategy that enhances resilience in one region can hinder it in another. For example, functional resilience in the GL was enhanced by managing for larger crown areas and greater variability in crown size, potentially due to the ability of a more closed canopy to regulate forest microclimate (Felipe-Lucia et al., 2018) by reducing incoming radiation and evaporative loss. In the SE, however, these same management activities slightly negatively impacted functional resilience, and resilience was instead enhanced by managing for greater variability in tree height (Figure S4 in Supporting Information S1). The strong regional dependence of forest stability emphasizes the need to tailor management practices based on the region and consider interactions with regional climate change when designing management plans.

Finally, we hypothesized that there would be a positive correlation between forest stability and structural complexity due to demonstrated connections between structural complexity and forest productivity and biodiversity (Dănescu et al., 2016; Fahey et al., 2015; Gough et al., 2019; Hardiman et al., 2013; Ishii et al., 2004). While this was true to an extent, for example, greater variability in tree height enhanced functional resilience in the SE, enhancing structural complexity was not uniformly associated with an increase in resilience. For example, higher variability in tree diameter was correlated with decreased functional resilience in the GL. This is likely influenced by limiting our definition of structural complexity to variability in tree height, diameter, and crown size, whereas the interaction between structural attributes is an important aspect of complexity (McElhinny et al., 2005). A holistic approach to describing structural complexity, such as using a metric encapsulating the three-dimensional spatial arrangement of vegetation, as presented by Zenner and Hibbs (2000) and Ehbrecht et al. (2017), would quantify complexity more objectively and facilitate comparison between regions and management types.

4.3. Study Limitations

While we acknowledge the critical role that natural disturbances play in shaping forest dynamics (Anderegg, Chegwidden, et al., 2022; Hicke et al., 2012; Pugh et al., 2019), this study does not explicitly evaluate the impacts of natural disturbances on forest structure and stability, nor how natural disturbances might intensify with climate change and interact with management to impact forest dynamics. This decision stems from the study's primary focus on understanding how management influences forest structure and how unforeseen interactions with shifting climatic conditions might affect the ability of management to enhance forest stability. To achieve this, we intentionally isolate key variables to disentangle these relationships, as introducing too many factors simultaneously would obscure these interactions. However, with climate change increasing the frequency and intensity of natural disturbances (Seidl et al., 2017; Turner, 2010), their exclusion here limits understanding of the potential effects of enhanced climate stress on carbon dynamics. Therefore, investigating the interplay of natural disturbances with management strategies presents a valuable avenue for future research, building on the foundational insights into this study.

5. Conclusions

This study examined the carbon cycle impacts of forest management, potential interactions with climate change, and consequences for forest stability. We adopted a multidimensional approach to evaluate stability, and in contrast to many previous studies evaluating forest management as a NbCS, included forest SOC, the largest forest carbon pool, in our analysis (Kaarakka et al., 2021). For forest management to be a viable NbCS, it must account for the durability of enhanced carbon sequestration and preserve existing carbon stores (Novick et al., 2024). However, accounting for durability concerns is challenging, as the risk to existing carbon stores depends on how forests respond to climate change. Our study demonstrated that management can increase forest resilience to climate change and minimize the release of stored carbon by reducing mortality. For example, mortality rates were highest under the control scenario, while simulations under all three management scenarios resulted in reduced mortality. Our findings highlight the regional dependency of management-induced changes in forest structure and resilience, as well as the dependence of temporal stability on regional climate change. For instance, high-intensity uneven-age management, which involves short rotation harvests across a large fractional area and understory thinning, enhanced functional resilience relative to the control in the SE but had the opposite effect in the GL. This emphasizes the point that forest management NbCS approaches are not universal, and that durability must be assessed at the regional scale. This information can help forest managers evaluate trade-offs between ecosystem goods and services, assess climate risks of applying management practices in different regions, and identify specific components of ecosystem function to bolster through targeted management practices.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The meteorology downscaling code is open-source and is available through the Predictive Ecosystem Analyzer (LeBauer et al., 2013). All ED2 codes for model initialization and analysis are archived on Zenodo (Fitzpatrick & Rollinson, 2023). National Ecological Observatory Network eddy covariance flux tower instrumentation and tower information is provided in the eddy covariance bundled data product (DP4.00200.001; NEON, 2024). The AmeriFlux FLUXNET data sets for UNDE (AmeriFlux site ID US-xUN; NEON, 2023a), TALL (AmeriFlux site ID US-xTA; NEON, 2023b), and OSBS (AmeriFlux site ID US-xSB; NEON, 2023c) adhere to the AmeriFluxdata use policy, CC-BY-4.0 License. National Ecological Observatory Network soil and vegetation data used for model initialization include soil physical and chemical properties collected from megapits (DP1.00096.001, NEON, 2023d), soil microbial biomass (DP1.10104.001, NEON, 2023e), and vegetation structure data (DP1.10098.001, NEON, 2023f).

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