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Research article

Private land management is more important than public land in sustaining oaks in temperate forests in the eastern U.S.

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ABSTRACT

Preserving the abundance and stocking of oaks (*Quercus* spp.) has become increasingly challenging in temperate hardwood forests of the eastern US in recent decades due to a remarkable shift in dominance to mesophytic species (e.g., red maple *Acer rubrum*). Studies have shown that efforts to sustain oaks while restraining maples yield limited success. Given that a significant portion of forestlands in the eastern U.S. are privately owned, it is critical to assess whether current forest management on cross-ownership forests can achieve those objectives. However, such assessments are rare. In this study, we employed a landscape modeling approach to investigate the long-term outcomes (i.e., 150-year forest composition and structure) of business-as-usual management and alternative management in a large, temperate hardwood forest landscape in Ohio, US. The business-as-usual management continues the current existing management practices, whereas the alternative management increases the pace and scale of forest management on both private and public lands to favor oaks. We compared the basal area and relative dominance for oaks (including *Q. alba*, *Q. coccinea*, *Q. prinus*, *Q. rubra*, and *Q. velutina*) and maples (including *A. rubrum*, *A. saccharinum*, and *A. saccharum*). Our results demonstrate that the implementation of business-as-usual management practices on both private and public lands may not effectively ensure the long-term sustainability of oak populations, but instead promote the proliferation of maple species over time. By contrast, alternative management on both private and public lands can effectively sustain oaks across a range of diameter classes while mitigating the growth of large, dominant maples. Our study emphasizes the influential role of private lands in driving oak-maple dynamics at the regional scale, as they can generate significant regional effects even when public lands continue with their business-as-usual management practices. Starting conditions based on landownership are crucial considerations for understanding these dynamics over time.

1. Introduction

Oaks (*Quercus* spp.) hold a dominant place in temperate deciduous forests in the US, providing critical ecological, economic, and aesthetic functions (Johnson et al., 2019). Oak genera have the highest species richness and comprise 20% of the total woody biomass of US forests (Cavender-Bares, 2016). Due to their abundance, oak-dominated ecosystems exhibit diverse structures and compositional features, supporting a high level of native floral and faunal diversity (Dey, 2014; Fox et al., 2010; Thompson et al., 2012). The leaves and debris from oaks are essential inputs for both terrestrial and aquatic ecosystems. They enhance productivity by supporting a greater diversity and amount of organisms involved in energy and nutrient cycles than those found in forested landscapes without oaks (Hansen, 2000; Stoler and Relyea, 2011). However, sustaining oaks (e.g., preserving their abundance and stocking) in the eastern US has become increasingly difficult in recent decades (Abrams, 2003; Dey, 2014).

Studies have revealed that many oak forests are undergoing a remarkable shift in species dominance. Oaks not only exhibit underrepresentation in smaller size classes, but also face a decline in overall abundance. This decline is accompanied with an increase in the importance of mesic species (e.g., red maple [*Acer rubrum*], sugar maple [*A. saccbarum*], and yellow poplar [*Liriodendron tulipifera*]) (Abrams, 1998; Fei et al., 2011; Fei and Steiner, 2007; Knott et al., 2019). Similar

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declines in oak abundance have been periodically observed in North America and Europe (Fei et al., 2011; Watt, 1919). These declines and dominance shifts are commonly attributed to various exogenous and unprecedented factors, such as altered fire regimes due to past fire suppression policies, climate change, land use change, insect and disease outbreaks, and modern wildlife and management practices (Bobiec et al., 2018; Demeter et al., 2021; McDaniel et al., 2021; Nowacki and Abrams, 2015). Understanding such oak decline and dominance shift is crucial for addressing their profound implications on forest biodiversity and ecosystem function, making it a key focus of research and management efforts (Oak et al., 2016; Palus et al., 2018).

Efforts to maintain oak stability have been carried out in recent decades, yet studies indicate limited success (Iverson et al., 2008; Schweitzer and Dey, 2011). This is probably because current conditions of oak forests have shifted outside their historical range often rendering some silvicultural treatments ineffective. For example, even-aged reproduction systems in the form of clearcutting were deemed useful for oak regeneration and implemented throughout much of the eastern US from 1960 through the 1980s (Carman, 2013; Roach and Gingrich, 1968; Sander and Clark, 1971). However, subsequent observations in post-harvest stands often found composition shifting away from oak domination towards a mix of hardwood species (Fischer et al., 1986; Swaim et al., 2018). Moreover, contemporary prescribed burns often fail to increase understory light conditions for the promotion of oak advanced reproduction pools (Arthur et al., 2012), which may eventually favor mesophytic competitors over oaks. For example, when compared to other species, unprecedented levels of red maple abundance have been reached in some parts of the eastern US, including prescribed burned areas (Fei and Steiner, 2007; Knott et al., 2019). Therefore, contemporary stand-level silvicultural treatments at their current frequency and intensity may no longer be effective for sustaining oak on the landscape. A much more progressive management alternative may be needed.

In the eastern US, approximately 57% of forestlands are under private ownership, with the remaining 43% belonging to government entities at the federal, state, and local level (Sass et al., 2020). Throughout much of the eastern US, dense human populations are embedded in forest-dominated landscapes that are managed (or unmanaged) by millions of private landowners. Moreover, these forestlands are fragmented in terms of size, the level of management practices, and owner's distinct motivations and interests. As a result, these forest landscapes exhibit significant differences in oak abundance, reflecting the diverse forms and intensities of forest management across the region (Duveneck and Thompson, 2019).

Forest ownership and corresponding management practices are major drivers of changes in the stand structure of deciduous temperate forests (Crow et al., 1999; Schaich and Plieninger, 2013a). Quantitative knowledge concerning both public and private ownership and their management practices is needed to guide long-term oak conservation strategy and policymaking. Recent studies have shown that the current management practices on public forests have limited impacts on sustaining oak abundance (Duan et al., 2023; Palus et al., 2018; Swaim et al., 2018). Given that a significant portion of forestlands are privately owned, it is critical to assess whether current forest management practices on those forests can also sustain oaks. However, such assessments are rare, particularly on private forests and with comparison to public ownership. Further, our understanding and concern for oak conservation concerns is typically based on research conducted primarily on public forests. As a result, ecologists and researchers have largely focused on providing input to management issues on public forests. However, failure to integrate private forests into oak-sustaining management and conservation planning in multi-ownership landscapes may result in big gaps for predicting species responses to management beyond the stand-scale.

Forest landscape modeling is an effective approach for disentangling and quantifying the effects of ownership and management on forest structure and composition across a landscape (Duveneck and Thompson, 2019). Forest landscape models can simulate seed dispersal by tracking the location and abundance of parent trees, as well as species biological traits that affect seedling establishment, growth, and mortality (He, 2008; Wang et al., 2014a). Some of these models also can simulate forest management practices that occur at the level of individual species, stands, and landscapes, and have been proven capable of examining the effects of different silvicultural alternatives for achieving desired management goals over large continuous spatial scales and long timespans (Duan et al., 2022; Duveneck and Thompson, 2019; Jin et al., 2018). Additionally, simulation modeling presents an effective way to disentangle compounding impacts through multiple scenarios with factorial designs (Duan et al., 2021; Gustafson et al., 2020).

In this study, we focused on temperate hardwood forests located in southern Ohio, USA, which are owned by various entities, including large areas of state and federal land, as well as numerous smaller privately owned woodlands. We used a spatial-explicit, forest dynamic landscape model, LANDIS PRO, to project changes in the top 26 abundant species over time under different management alternatives to address the following research questions: 1) Can current management on private and public lands successfully sustain oaks while restraining maples? If not, can an alternative management approach that increases the pace and scale of active management achieve these objectives? 2) Can management on private lands have regional effects? 3) What are the relative contributions of alternative management on private and public lands to sustaining oaks and restraining maple at the regional scale?

2. Material and methods

2.1. Study area

The study area is located in southeastern Ohio, north of the Appalachian Mountain range, and covers approximately 2.1 million hectares of the Southern Unglaciated Allegheny Plateau ecological section

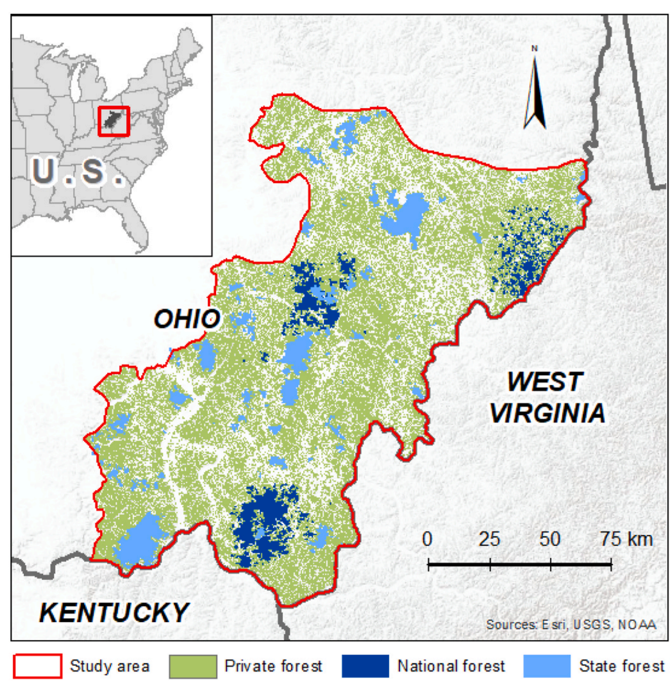

Fig. 1. Location of the study area (outlined in red). The color green indicates private forests, while the color blue indicates public forests. Specifically, the Ohio Department of Natural Resources State Forest lands are represented by light blue, and the Wayne National Forest is represented by dark blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 1). Specifically, the study area is intersected with five ecological subsections, namely Ohio Valley Lowland (221Ec), East Hocking Plateau (221Ed), Unglaciated Muskingam Plains (221Ee), Western Hocking Plateau (221Ef), and Lower Scioto River Plateau (221 Eg). This region has a humid continental climate, characterized by hot, humid summers and cool winters (Owenby and Ezell, 1992). The annual average precipitation and temperature range from 810 to 960 mm and from 10.2 to 12.8 °C, respectively. The soils in this area are well-drained or moderately well-drained and have fine, loamy textures, formed from sandstone, shale, siltstone, and limestone (Pearcy et al., 1999). This study area is predominantly forested, comprising 67% of the total land cover, with broadleaf deciduous tree genera such as oak (*Quercus* spp.), hickory (*Carya* spp.), maple (*Acer* spp.), and beech (*Fagus* spp.). The USDA Forest Service National Forest System (i.e., Wayne National Forest, WNF) manages 5% of the study area, while the state agency (i.e., Ohio Department of Natural Resources, ONDR) manages 7.5% of the land. Most of the remaining forests in this study area are in private ownership, resulting in a mosaic and fragmented forest landscape that is comparable to other forestlands in the eastern United States.

Public lands experienced relatively rigorous fire suppression practices prior to the 1970s, which have facilitated the abundance of red maple in understory layers (Fei and Steiner, 2009). Additionally, the management objectives for public lands focus on sustaining oak-dominant forests, implementing strategies that ensure a varied range of tree ages and sizes, and promoting or preserving plant species that hold substantial value for a diverse array of wildlife (Widmann et al., 2014). In contrast, historical management on private lands exhibit notable diversity and complexity, shaped by a range of factors including landowner motivations and management costs. Landowners who prioritize short-term profit use more intensive harvesting practices, such as high-grading that harvest the largest and most valuable trees. These practices have a significant impact on species composition and age structure (Ward et al., 2005).

2.2. Modeling approach

We employed the species-specific, forest landscape model LANDIS PRO to simulate forest dynamics and forest management practices. LANDIS PRO model is a process-based model and it is designed with the capability to simulate the demography of individual species (i.e., number of trees of age cohort) and stand dynamics within each grid cell, while also simulating landscape processes, such as seed dispersal, harvest, fire, and windthrow as contiguous spatial events across the region (Duan et al., 2022; Fraser et al., 2013; Wang et al., 2014a). This model has been extensively calibrated with USDA Forest Service, Forest Inventory and Analysis (FIA) data (O'Connell et al., 2014) and has been applied in multiple eco-regions across the eastern United States (Brandt et al., 2014; Duan et al., 2022; Wang et al., 2019). We developed two levels of management for sustaining oak and restraining maple on private and public forests: (1) business-as-usual (BAU): forest lands of each ownership continue with current business-as-usual forest management practices; (2) alternative management (AltMgt): forest lands of each ownership are more intensively management. The detailed management practices are described in Sections 2.4 and 2.5. Furthermore, we used a two-way factorial experimental design with two levels of management (i.e., BAU and AltMgt) and two levels of ownership (i.e., private and public forest) as factors to evaluate the effects of forest management for sustaining oak and restraining maple at regional scales. This experimental design allows us to explore potential interactions (e.g., seed sources, landscape arrangements) between private and public forests and determine whether the management practice in one region influences the dynamics in the other. We labeled the four scenarios as S1 (BAU on both private and public lands), S2 (AltMgt on both private and public lands), S3 (BAU on private lands while AltMgt on public lands), and S4 (AltMgt on private lands but BAU on public lands).

2.3. LANDIS PRO model parameterization and calibration

We modeled the top 26 most abundant tree species based on their basal area from FIA data, while also including species of ecological or economic importance or those with significant canopy potential. In addition, we added a pseudo-species to encompass all other species present on the landscape but that did not meet the specifications above to be simulated at the species level (Table S1). The species' demographic processes, such as tree growth, maturity, sprouting, establishment, and mortality, were driven by their specific biological traits, which we parameterized based on previous studies (Duan et al., 2022, 2023; Wang et al., 2014a). To develop a starting forest condition composition map for LANDIS PRO, we utilized FIA data from 2000 to 2010 and classified land cover data from the National Land Cover Database in Landscape Builder (Dijak, 2013). The initial condition map has tree numbers and age cohorts in every raster grid cell, along with the corresponding land cover type configuration (Wang et al., 2014a). We used the same initial forest condition for the four scenarios and ran the model from 2010 to 2160, using 10-year time steps at a 90-m resolution. We ran 10 replications for each scenario to capture uncertainty resulting from stochasticity in the models. We evaluated the simulation results for species basal areas, densities, and successional trajectories at both stand and regional scales, based on the framework proposed by Wang et al. (2014b), by comparing them with data obtained from FIA data in 2010–2020 and previous research conducted on old-growth forests within the study area (Goebel and Hix, 1996).

We separately parameterized BAU management on public lands (i.e., national and state forest lands) and private lands to reflect management practices occurring over the last 10 years. Meanwhile, we assumed both the area and number of private and public lands are constant throughout the simulation period. All management parameters and scenarios were implemented in the LANDIS PRO Harvest Module. Refer to Fraser et al. (2013) for more detailed information on the harvest prescription simulation in LANDIS PRO.

2.4. Business-as-usual (BAU) management on private and public lands

We compiled the BAU management parameters on private lands by harvest methods based on the data extracted from FIA Ohio report (Widmann, 2016) and LANDFIRE (LANDFIRE, 2018). LANDFIRE raster data is forest disturbance data interpreted from satellite imagery representing forest disturbance including forest harvesting over a 10-year period (LANDIFIRE, 2018). One of the disturbance classes is mechanical removal which we interpreted as harvest. These removals are classified into 3 severity classes low, medium, and high, and are listed as having occurred in the last year, 2–5 years ago, and 6–10 years ago, respectively. We interpreted the severity classes as low severity being forest thinning, moderate severity being shelterwood harvest, and high severity being clearcut harvest. Since light harvest (typically high grading or single tree selection) is difficult to identify on satellite imagery used for the LANDFIRE data, therefore we used the LANDFIRE data to estimate more intensive harvests (i.e., clearcut, shelterwood, and heavy thinning). We further subdivide this information by ecological subsection.

Based on the estimates from Widmann (2016), there are approximately 143,460 ha treated per decade in our study area. LANDFIRE data indicated that there is 38,022 ha treated by more intensive harvest, thus, the area treated by light harvest is 1,105,438 ha per decade on private lands. These hectarages were proportioned out to subsections based on area estimates of each subsection. Based on numbers provided by the National Woodlands Owner Survey, 29% of lands harvested are done with the guidance of a professional forester and 71% are not. So treated areas by subsection were further portioned by whether they used a professional forester or not (Table S2). We assumed that harvest with the guidance of a forester emphasized retaining oaks in the residual stand whereas harvest without a forester removed the merchantable oaks and left less commercially desirable species, which is based on local land management reports (e.g., Widmann, 2016) and our understanding of common challenges faced by private landowners.

For the public lands on the WNF, the management records for the period 2010–2020 were obtained from the USDA Forest Service Timber Harvests database. To minimize the number of individual activities needed to parameterize management in LANDIS, the hectarages of small and large treatments were combined using these data. The percentage of areas that received silvicultural treatment in each administration unit was then summarized as the BAU scenario on NF (as shown in Table S2). Approximately 1.6% of the WNF received the same type of silvicultural management over the 2010–2020 period. For the public lands held in state forests ownership, we used silvicultural data from 2009 to 2015 provided by the Ohio Department of Natural Resources (ODNR) to establish clearcut, even-aged, and uneven-aged regeneration cut hectarages. The total treated area on public lands was 118,322 ha, which represents approximately 7.3% of the total available management area (Table S2).

2.5. Alternative management (AltMgt) on private and public lands

We developed hypothetical management practices in AltMgt, which encompass the essential elements of practical silvicultural methods. Our goal in creating these alternative management strategies was not only to project the results of such practices but also to conduct an experiment that would provide valuable insights into the landscape. For AltMgt on private lands, we assumed that all private lands are managed with the guidance of professional foresters and the treated area doubled compared to the BAU management practices. Furthermore, harvest species preferences would align with the recommendations of these professional foresters, which emphasize the prioritization of maple harvesting over oak within each silvicultural treatment.

For the AltMgt on public lands, we designed a shelterwood harvesting method, which involves multiple rounds of partial harvesting to systematically replace mature trees with new growth. The first round of harvesting removed select midstory trees, primarily maples and non-oak species, to improve the vigor and abundance of young oak trees and a subsequent round of harvesting further opened the canopy. Besides the shelterwood method, we also implemented periodic thinning that targeted maples, limiting their seed production and promoting oak regeneration. Beginning in 2020, the modeled management approach implemented silvicultural treatments every 10 years on 10% of public forest lands, including national and state forests. This rate of treatment was higher than current practices. The specific details of the treatments are provided in Table S3.

2.6. Data analysis

We conducted a simulation of two levels of management on both private and public lands for 150 years into the future and evaluated the performance of each management scenario based on species-level basal area and relative dominance. Basal area was calculated using the diameter at breast height (DBH) and tree density, while relative dominance was computed as the species basal area divided by the total basal area of all species. To visualize the effects of the different management scenarios over time, we compared the mean basal area and mean relative dominance for selected species. We also represented the percentage of the landscape area by mean-DBH class to highlight the differences in diameter distributions of trees among public and private lands. To assess changes of species composition at the regional scale, we used the regional basal area of distinct oak species (white oak, northern red oak, black oak, chestnut oak, and scarlet oak, collectively referred to as oaks) and maple species (red maple, sugar maple, and silver maple, collectively referred to as maples). We utilized the basal area as an indicator, recognizing that while basal area provides a measure of density and dominance, it may not fully capture the nuances of tree size distribution. The regional basal area values were employed as explanatory variables for the management effects on private and public lands.

We used the method proposed by Temperli et al. (2013) to calculate the effect size of AltMgt on regional oaks basal area on private and public lands and their interaction. The effect size of AltMgt on private lands (α) was calculated as the difference of regional oak basal area between S4 and S1 (i.e., α = S4–S1). Similarly, the effect size of AltMgt on public lands (β) was calculated as the difference of regional oak basal area between S3 and S1 (i.e., β = S3–S1). The interactions (δ) were determined by subtracting both α and β from S2–S1 (i.e., δ = S2–S1-α-β). The relative contributions of alternative management on private and public lands were calculated by dividing each effect size (i.e., α, β, δ) by the total effects size (i.e., $\alpha+\beta+\delta$). Additionally, we estimated the AltMgt effect sizes on maples at the regional scale by utilizing the basal area of maples.

3. Results

3.1. Effects of BAU and AltMgt on private and public lands

For both private and public lands, species basal area and relative dominance of different tree species exhibited different responses under BAU and alternative management. Under BAU management, the total basal area of oaks experienced a slight increase and remained relatively stable during the first century but then declined on both private and public lands. In contrast, the total basal area of maples exhibited a dramatic increase, rising from less than 4 m^2/ha to approximately 20 m^2/ha over the projected 1.5 centuries (Fig. 2a, b, 2g, 2k). Moreover, maples progressively gained a larger proportion of total dominance throughout the simulation with red maple comprising the majority. By the year 2160, maples accounted for more than 50% of the total relative dominance, compared to less than 20% in 2010 (Fig. 3a, b, 3g, 3k). In contrast, oaks comprised approximately 22% and 26% of the total relative dominance on private and public lands, respectively (Fig. 3a, b, 3g, 3k).

Under the alternative management, the basal area of oaks on private lands increased to over 8 m^2/ha and remained relatively stable at this level until 2160 (Fig. 2d and j), occupying approximately 20% of total relative dominance (Fig. 3d and j). While the oaks' basal area and relative dominance on public lands were over 12 m^2/ha and 27% by the end of the simulation (Fig. 2e, h, 3e, 3h). Additionally, the basal area of maples increased to more than 11 m^2/ha on private lands and exceeded 10 m^2/ha on public lands, remaining at these levels until 2160 (Fig. 2d, e, 2h, 2j). The relative dominance of maples fluctuated between 23% and 33% (Fig. 2j and k).

Shade-intolerant species such as bigtooth aspen, yellow poplar, and black locust, experienced a significant reduction of approximately 50% in their total basal area under the BAU management on both private and public lands (Fig. 2a, b, 2h, 2k); however, under the alternative management, these species expanded to 1–15 times their initial basal areas (Fig. 2d, e, 2h, 2j). In contrast, shade-tolerant species like elms, hickories, beech, and hemlock were suppressed by more competitive maples under BAU management, occupying 17% of the total dominance on both private and public lands by 2160 (Fig. 3a, b, 3g, 3k). Under the alternative management, shade-tolerant species represented over 25% and 15% of the relative dominance on private and public lands, respectively (Fig. 3d, e, 3h, 3j).

There was a large shift in the distribution of mean diameters of oaks and maples to larger diameter classes from 2010 to 2160 under different management types. Private and public lands presented slightly different DBH compositions for both genera in the initial year (i.e., 2010). In 2010, most oaks occurred between the 25–40 cm DBH classes (Fig. 4a and c). Under the BAU management, oaks grew and occupied high abundances in the over 70 cm DBH classes on both private and public lands (Fig. 4a and c). In contrast, over the 150-year period, the AltMgt spread the diameter of oaks across the entire distribution on both private

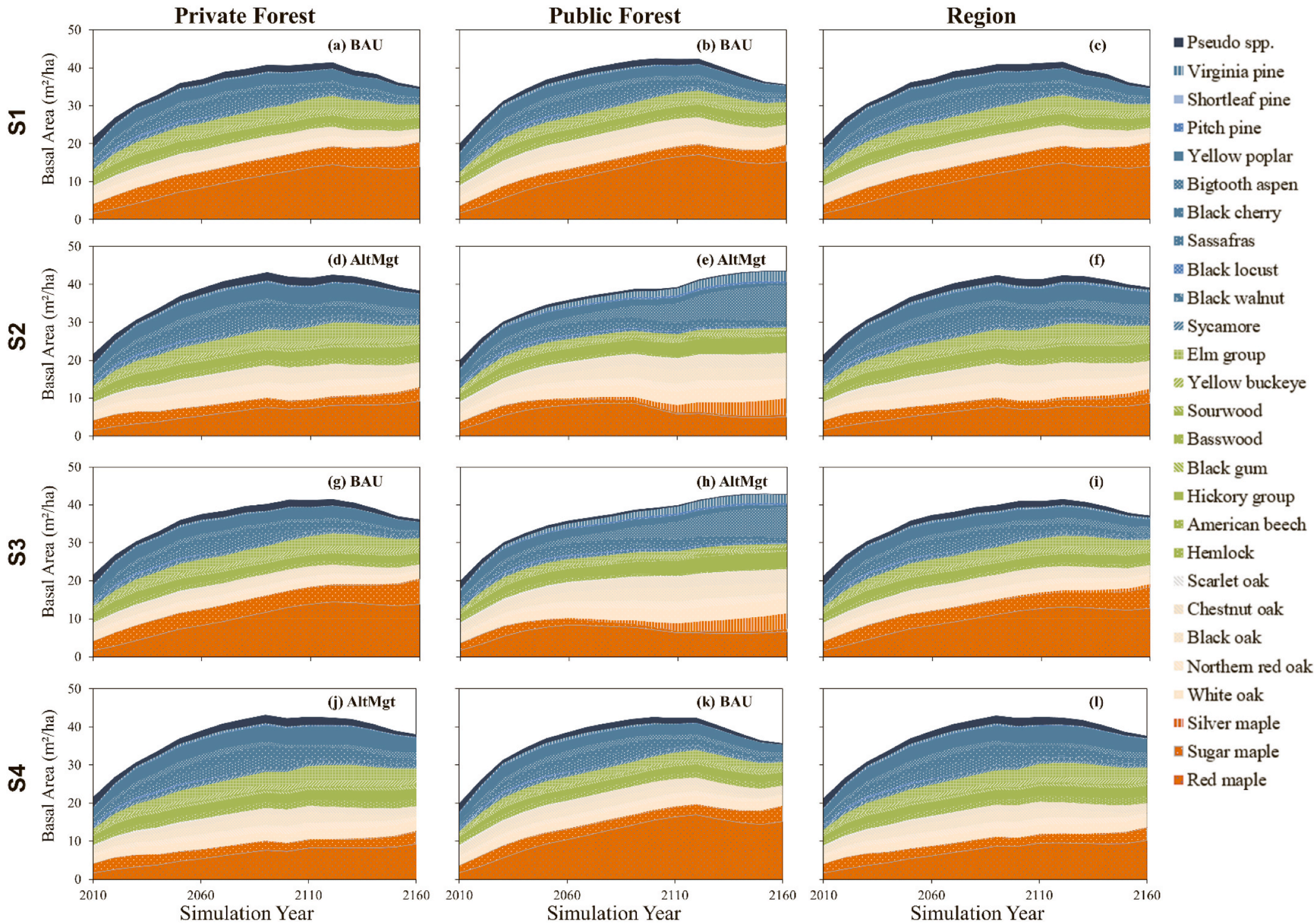

Fig. 2. The basal area of 27 species under the 4 simulation scenarios, namely S1 (private forest BAU + public forest AltMgt), S2 (private forest AltMgt + public forest AltMgt), S3 (private forest BAU + public forest AltMgt), and S4 (private forest AltMgt + public forest BAU). Plots on each row are results for a specific simulation scenario. The first two columns are the basal area of private forest and public forest under designated management, respectively. The last column is the basal area of the entire study area for each scenario. Oaks are in creamy white, and maples are in amber. Pine and shade-intolerant species are in blue while shade-tolerant species are in green. Specific species can be identified by different filling patterns. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and public lands (Fig. 4a and c). The reverse-J DBH distribution of maples in 2010 shifted to a right-skewed bell-shaped distribution in 2160 under the BAU, while maple distribution retained its reverse-J distribution under the alternative management (Fig. 4b and d). The AltMgt restrained maples at relatively small DBH classes (i.e., <15 cm) when compared to BAU (Fig. 4b and d).

3.2. Effects of BAU and AltMgt regionally

At the regional scale, total basal area of all species (Fig. 2c, f, 2i, 2l) and relative dominance (Fig. 3c, f, 3i, 3l) had different patterns under different scenarios. Under the S1 scenario (i.e., BAU management on both private and public lands), the regional total basal area of oaks shrank from 4.87 m^2/ha with 22.8% dominance in 2010 to 3.75 m^2/ha with 12% dominance in 2160 after 150 years of contemporary low management levels (fig.s. 2c and 3c, S1a). Maples expanded immensely during this period, from 4.1 m^2/ha to 20.4 m^2/ha with 58% relative dominance at the end of the simulation (figs. 2c and 3c, S1b). The basal area of early successional species such as yellow poplar, bigtooth aspen, etc. decreased from 5.4 m^2/ha with 25% dominance to 4.0 m^2/ha with 11% dominance by 2160.

Under the S2 scenario (i.e., AltMgt on both private and public lands), the regional total basal area of oaks increased from 4.87 m^2/ha to 7.34 m^2/ha with stable dominance around 20% by 2160 (Figs. 2f and 3f). Although the public lands received AltMgt under the S3 scenario, the patterns of regional basal area and relative dominance presented similar patterns with S1, where oaks shrank their dominance while maple expanded dramatically (figs. 2i and 3i, S1c). As a comparison, even though only private lands received AltMgt under the S4 scenario, the total basal area and relative dominance of oaks in the region can still be stabilized at ~5 m^2/ha and ~18% respectively, while maples did not become overwhelmingly dominant (Figs. 2l and 3l, S1d).

Regionally, the diameters of oaks were concentrated around >70 cm DBH class after 150 years of BAU on both private and public lands; however, they were more evenly distributed, especially in small and medium diameter classes (i.e., 10–60 cm) if both private and public lands receive AltMgt (Fig. 4e). The DBH distributions of maples under different management in 2160 did have notable differences when summarized regionally. The diameters of maples were clustered around 10–15 cm DBH class in 2010 and grew to the 50–65 cm DBH class after 150 years of BAU management (Fig. 4f).

3.3. Relative contribution of private and public lands management regionally

The relative impact of private and public land management on the

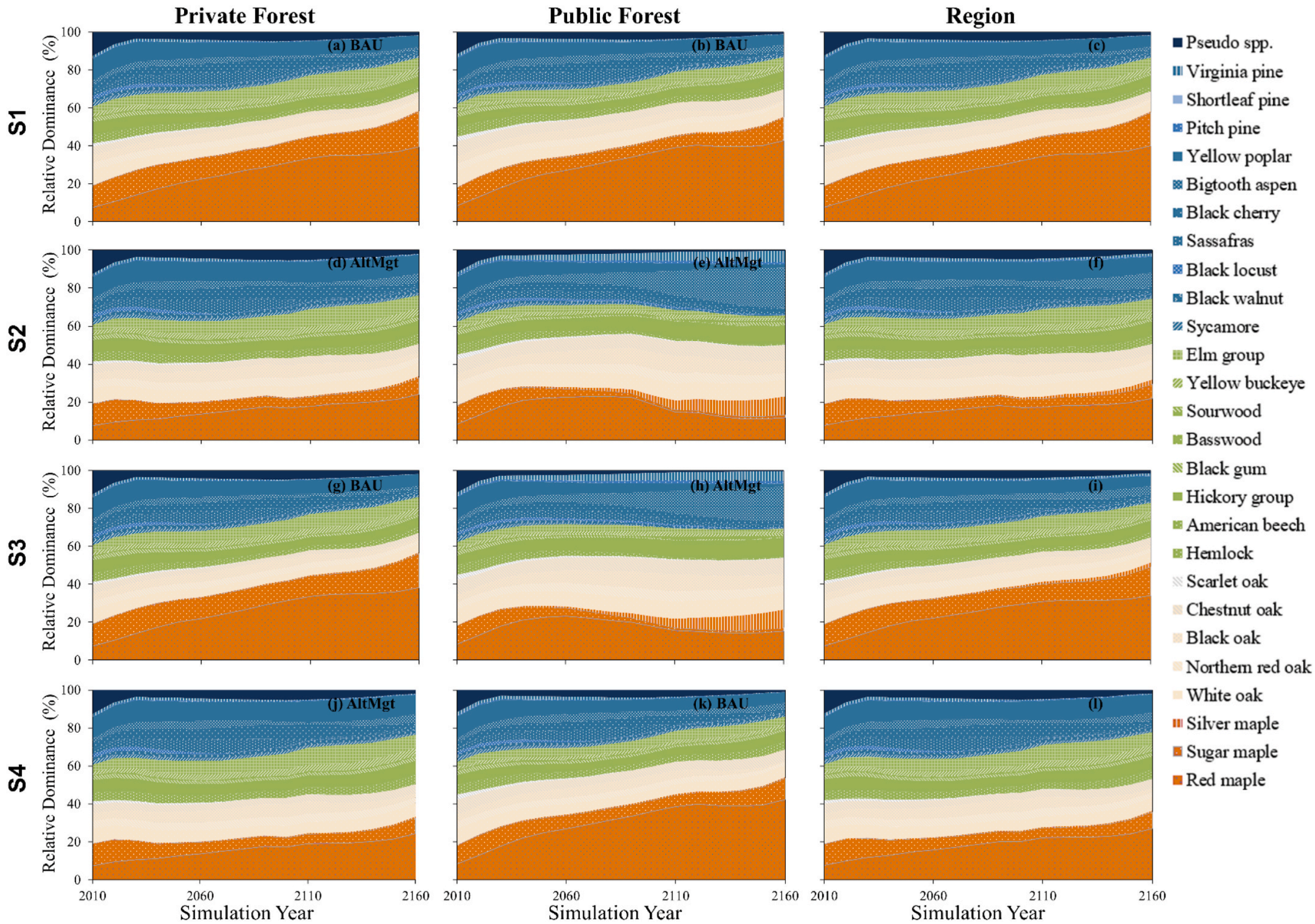

Fig. 3. The relative dominance of 27 species under the 4 simulation scenarios. Plots on each row are results for a specific simulation scenario. The first two columns are the relative dominance of private forest and public forest under designated management, respectively. The last column is the relative dominance of the entire study area for each scenario. Oaks are in creamy white, and maples are in amber. Pine and shade-intolerant species are in blue while shade-tolerant species are in green. Specific species can be identified by different filling patterns. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

structure and composition of oaks and maples varied regionally throughout the 150-year simulation. In 2020, despite private lands comprising ~80% of the study area, the implementation of AltMgt on these lands accounted for more than 97% of oak management effects. In contrast, occupying around 20% of the area, public lands contributed less than 3% to oak management effects. By 2160, the relative contribution of private lands gradually decreased to ~65%, while public lands increased to over 30% (Fig. 5a). While public lands demonstrated an increasing contribution over the simulation period, it is evident that management on private lands plays a critical role when compared to public lands. In terms of maple basal area, the combined contribution of private and public lands exceeded 95% on average, with private lands contributing around 83% throughout the simulation (Fig. 5b). Overall, our results indicate that the management on both private and public land play significant roles in driving regional changes in oak-maple dynamics, with private lands holding a dominant position.

4. Discussion

This study aims to evaluate the long-term effects and contributions of land management practices in promoting oak sustainability and mitigating maple dominance across private and public landownerships in temperate forests of the eastern US. We employed a spatially explicit and dynamic forest landscape model to project forest composition and structure from 2010 to 2160. We compared the simulated outcomes for oaks (including white oak, northern red oak, black oak, chestnut oak, and scarlet oak) and maples (including red maple, sugar maple, and silver maple) based on different combinations of land ownership and management alternatives. According to our model results, if current BAU management practices persist, maple basal area is projected to increase by more than fivefold, accompanied by a doubling in relative maple dominance on both private and public lands. Meanwhile, increasing the frequency and extent of active forest management on both private and public lands can effectively sustain oaks across a range of diameter classes while mitigating the growth of large, dominant maples (Albrecht and McCarthy, 2006; Iverson et al., 2017). Our study highlights the influential role of private lands in driving the dynamics between oaks and maples, as they can generate significant regional effects even when public lands continue with their BAU management practices. These findings underscore the importance of management activities on private lands in affecting the abundance of oaks and maples at a regional level.

Our findings indicate that the implementation of BAU management practices on private lands may not effectively ensure the long-term sustainability of oak populations, but instead promote the proliferation of maple species over time, thereby undermining the intended management objectives. In the eastern US, a significant portion of oak forests has experienced limited or no management for nearly a century

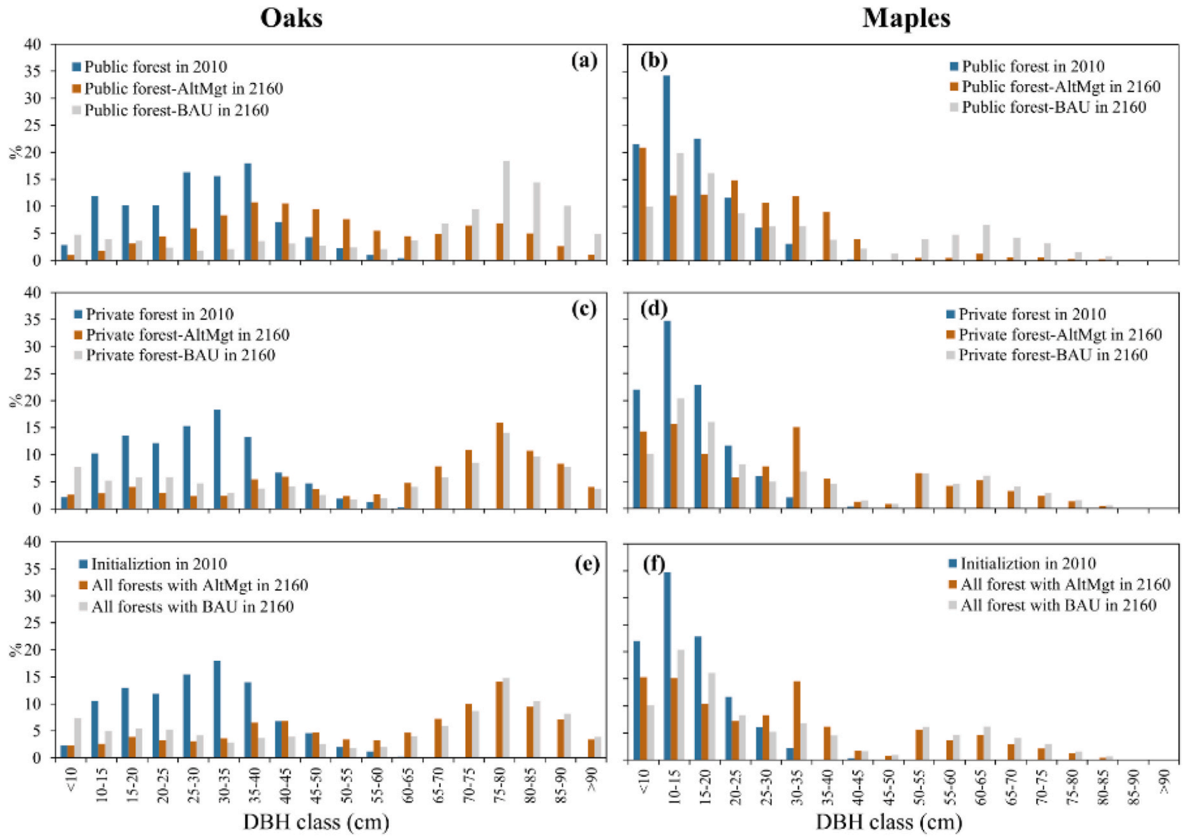

Fig. 4. Comparison of (a) public forest oaks', (b) public forest maples', (c) private forest oaks', (d) private forest maples', (e) regional oaks', and (f) regional maples' DBH distribution in 2010 and 2210 under business as usual (BAU) and alternative management (AltMgt). The x-axis is the DBH class, and the y-axis is the percent of the stands in each diameter class. Stands are the smallest identified treatment unit to which harvest operations are applied in LANDIS.

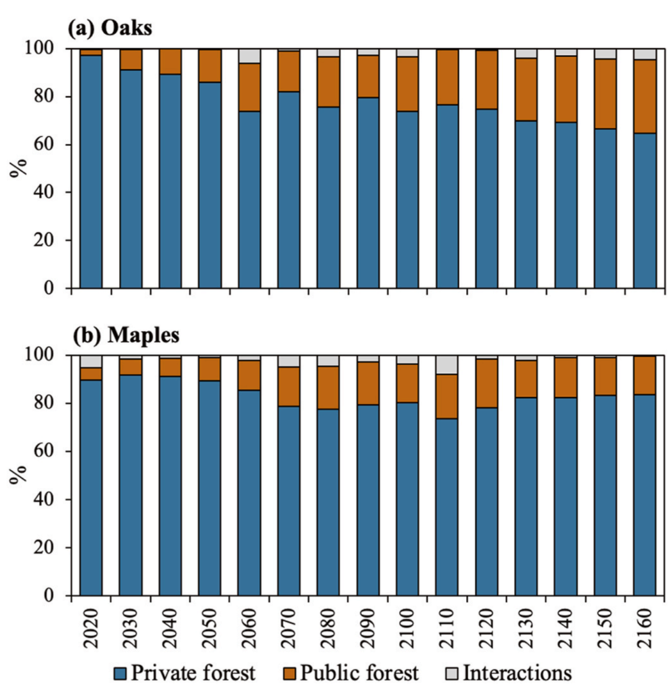

Fig. 5. Relative contribution of private forest, public forest, and their interactions (i.e., interactive effects of the private and public forest) through time on regional oaks (a) and maples (b) basal area under alternative management (AltMgt).

(Hanberry et al., 2020). The current composition of midstory vegetation in these oak forests is characterized by the overwhelming presence of rapidly growing mesophytic species, particularly red maple and sugar maple. This dominance is partially driven by the faster growth characteristics of maples, which, being shade-tolerant, outcompete other species for available resources. Additionally, the light-demanding nature of specific oak species further complicates the dynamics (Brose and Rebbeck, 2017). Maples' ability to thrive in shaded conditions contributes to the formation of a dense midstory canopy, restricting sunlight from reaching the forest floor. This lack of adequate light poses a challenge to the regeneration of light-demanding oak species, hindering their successful establishment and growth during forest succession. Additionally, prevalent exploitative harvesting practice (i.e., high-grading) on private lands occurs within the BAU management and has been suggested to contribute to the decline in oak abundance (Curtze et al., 2022). Our study reveals a significant absence of oak trees in the sapling and midstory size categories, reflecting challenges not only in the survival of oak saplings (e.g., 10–20 cm in DBH) but also in the establishment and growth of oak seedlings (e.g., DBH <10 cm) (Fig. 4a and c), despite the continued growth of mature overstory oaks with a DBH of 40 cm or greater. These results (Fig. 4) are supported by other field-based studies (Arthur et al., 2015; Dyer and Hutchinson, 2019; Iverson et al., 2008; Palus et al., 2018).

Our study demonstrates that the alternative management on both private and public lands (i.e., maple-prone harvest on private lands while shelterwood and thinning on public lands) could help to achieve the management objective of sustaining oaks and restraining maples by altering species composition and diversifying size-class structure. On private lands, the alternative management facilitated an increase in mid-size class maples and a reduction in juvenile maples (DBH <25 cm, Fig. 4), which may mitigate competition pressures exerted upon oak saplings and seedlings than BAU management (Palus et al., 2018; Schweitzer and Dey, 2011). In contrast to the BAU management prescription, the alternative management strategy implemented on public lands involved multi-entry shelterwood harvests and selective harvests specifically targeting red maple. As a result, this approach maintained relatively consistent levels of oak and maple abundance over the 150-year simulation (Fig. 4). Additionally, alternative management on public lands resulted in greater proportions of oak in smaller size classes and higher size-class diversity (Fig. 4), representing a sustainable oak structure that public forests aim to achieve (e.g., Ohio Department of Natural Resources, 2020; Wayne National Forest, 2006).

Our study shows that the relative impacts of management on private and public lands are changing over time, with a decrease on private lands and an increase on the public lands. This change can be influenced by several interacting mechanisms such as management policy and regulations, and resource allocation. For example, private lands may be subject to different policies or regulations, affecting the feasibility and impact of management practices that favor oaks (Butler et al., 2021). On the other hand, public lands often operate under specific regulations and guidelines that prioritize ecological health, sustainability, and services, potentially amplifying the positive impact of management efforts in the long term.

The relative impacts of interactions between private and public cannot be neglected in our study. The underlying mechanisms that cause these interactions include the seed sources, dispersal processes, and the landscape spatial heterogeneity. For example, public forests under alternative management may act as seed sources for oak regeneration, potentially influencing the oak basal area in adjacent private lands. Similarly, private lands under alternative management may contribute to a higher seed availability and subsequent oak establishment in public lands. This bidirectional seed dispersal and establishment process could result in an interactive effect. The spatial arrangement and connectivity of private and public lands can also contribute to the observed interactions. Variations in spatial configuration and connectivity of oak and maple trees in private and public forests can affect the range of seed dispersal, leading to varying management effects across the landscape (Rendenieks et al., 2015).

Our study provides evidence that management practices on private lands have significant regional effects, surpassing those on public lands. While the substantial difference in forested area between private and public ownership types is a contributing factor (Schaich and Plieninger, 2013b), it is also crucial to stress that the reasons for this disparity are multifaceted. Historical management practices, diverse environmental conditions, and landowner attitudes all play roles in shaping the observed regional effects. Despite private lands having a larger land area, their relative contribution does not align proportionally with their size, underscoring the intricate interplay of various factors in influencing landscape-level dynamics. For instance, although private lands account for approximately 80% of the total area, their management effects decrease to 65% over the 150-year timeframe, while the effects of public lands increase to over 30%. Therefore, when developing alternative management plans from a regional perspective, it is crucial to consider the long-term consequences of such plans, particularly not underestimating their cumulative effects on public lands.

Our modeling results facilitate the exploration of BAU and alternative management and their long-term outcomes on large continuous landscapes. Previous studies have primarily focused on assessing the impacts of private land harvest, typically high-grading, on forest structure and composition using small samples with limited geographic extent (Anderson-Teixeira et al., 2013; Rogers et al., 2018; Ward et al., 2005). The effects of alternative management could be long-lasting and may require decades to manifest for regional outcomes to be fully evaluated. For instance, the implementation of stand-level multi-entry shelterwood, a widely recommended silviculture method for promoting oak regeneration, typically necessitates 10–50 years to establish an adequate number of large oak advance reproduction (Johnson et al., 2019). Such a timeframe often exceeds the timeframe of most field-based studies. Our model simulations operated at the landscape scale, enabling assessments of the cumulative impacts of current and alternative management on oak regeneration and development. These assessments provide evidence-based supports for oak conservation and policy design (Brandt et al., 2014).

Our findings also suggest that the implementation of alternative management on private lands requires considerable time to yield desired outcomes. Private landowners face trade-offs between oak-promoting management and BAU management, considering factors such as resource investment, aesthetic preference, recreational needs, and conflicting land management objectives (Butler et al., 2021). These trade-offs sometimes outweigh perceived benefits, potentially impeding long-term commitments (Knoot et al., 2010). For example, survey data highlights the logistical challenges of persuading private landowners to embrace oak-promoting management, even when they recognize the ongoing oak decline in the region (Knoot et al., 2010). Various policy instruments, including incentive programs and stewardship programs, are recognized as potential mechanisms to provide cost-share assistance, thereby alleviating the economic burden associated with implementing oak-promoting management and ultimately encouraging participation by private landowners (Butler et al., 2014). Although our study did not involve direct financial assistance to landowners, we referred to these programs as conceivable policy instruments that could ease the economic burden for private landowners undertaking oak-promoting management. Besides the financial assistance, our study revealed the feasibility of altering oak maple composition at landscape scales by engaging private landowners to promote oak-promoting management. Although we did not conduct a specific cost-effectiveness analysis in this study, our aim was to emphasize the feasibility of driving changes in forest composition on private lands. These findings contribute to our comprehensive understanding of developing long-term forest management plans at the regional level.

Our study focused on the environmental conditions under the current climate, however, studies show that climate change has been significantly impacting forest composition in the eastern United States (Fei et al., 2017; Knott et al., 2019; Pederson et al., 2015). Changes in climate could affect the long-term validity and applicability of our projected forest composition and management effects. For example, higher mean annual temperatures and reduced precipitation may favor oak on xeric stands, as oaks are relatively more tolerant than their competitors. Decreases in climatic moisture may increase the future potential for fires, facilitating the use of prescribed fires to promote oak growth. Thus, future studies should consider the potential influence of climate change and incorporate it in their analyses and interpretations.

CRediT authorship contribution statement

Shengwu Duan: Writing - original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Hong S. He:** Writing - review & editing, Software, Funding acquisition, Conceptualization. **Lauren S. Pile Knapp:** Writing - review & editing. **Thomas W. Bonnot:** Writing - review & editing. **Jacob S. Fraser:** Writing - review & editing, Software, Methodology.

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

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.120013.

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