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# Current management in national and state forests has important but limited impacts on sustaining oaks in temperate forests of the eastern U.S

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ABSTRACT

Active management for promoting oaks (*Quercus* spp.) and restraining maples (*Acer* spp.) is mostly conducted in public forests (e.g., national forests [NF] and state forests [SF]) because of oaks' ecological and economic importance. Studies have shown that current management efforts have limited success, meanwhile, oak-dominant forests continue to shift in composition and structure to shade-tolerant, fire-sensitive mesophytic species (e.g., red maple *A. rubrum*). It remains to be evaluated whether current management can achieve its objectives in public forests and at regional scales. In this study, we investigated the long-term outcomes of business-as-usual (BAU) and alternative management (AltMgt) scenarios in a large, temperate hardwood forest landscape in southern Ohio, US. The BAU approach simulates contemporary management, informed by harvest records across public lands and a geospatial disturbance database (i.e., LANDFIRE) to infer private land management. Whereas the AltMgt scenario increases the pace and scale of forest management on public lands through two-stage oak shelterwood harvests, treated every ten years across 10% of the land area with private land remaining as BAU. We used a spatially explicit and dynamic forest landscape model to project species compositional and structural changes under these two scenarios. Our results demonstrate that BAU management in public forests may not successfully sustain oak but instead favors the colonization of maples. Further, management objectives to promote oaks could be achieved on public forests under the AltMgt scenario, but such alternative management had limited impacts at the regional scale when including private lands. The management of NF and SF has a crucial role in driving regional changes in oak and maple abundance, particularly when private lands continued their BAU management. Starting conditions by landownership are also important considerations for oak-maple dynamics through time, implying the need to have a range of priorities and objectives, under different time frames, when developing long-term conservation plans for oak forests at regional-scales.

## 1. Introduction

Oaks (*Quercus* spp.) are important components in the temperate forest biome of the United States (US), providing critical ecological and economic functions (Cavender-Bares, 2016). >60 oak species are growing in the continental US (Mabberley, 2017). There are 28 oak-related forest types in the Eastern US, representing 51% of all forest-lands (78.5 million ha) and about 45% of the total growing stock volume (Johnson et al., 2019; Oswalt et al., 2019). Historically, periodic, low- to moderate-intensity anthropogenic surface fires maintained upland oak dominance by reducing competition from fire-sensitive species and maintaining a highly flammable herbaceous fuel bed (Abrams, 1992).

Over the last century, however, eastern US oak-dominant forests continue to shift in structure and composition to shade-tolerant, fire-sensitive mesophytic species (e.g., *Acer rubrum*) (Abrams, 1992, 2003; Fei and Steiner, 2007; Knott et al., 2019; Oak et al., 2016). This shift is often attributed to fire suppression policies implemented in the early 20th century and corresponding changes in fire regimes (Hutchinson et al., 2005; Nowacki and Abrams, 2015). Oaks are increasingly underrepresented in forest understory (Miller and McGill, 2019; Vickers et al., 2019). Even worse, the occurrence of natural or anthropogenic disturbance-caused canopy openings under certain conditions can promote the growth of more opportunistic species, such as sweetgum (*Liquidambar styraciflua*), tulip poplar (*Liriodendron tulipifera*), and

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sassafras (*Sassafras albidum*) in the understory (Alexander et al., 2021; Iverson et al., 2017). The continuing decline in oak abundance may lead to irreversible transitions in forest composition, generating concern about the long-term consequences for ecosystem function. (McEwan et al., 2011; Nowacki and Abrams, 2008).

Studies show that efforts to restore oaks have limited success (Iverson et al., 2008; Schweitzer and Dey, 2011). Current timber harvests in oak forests typically focus on removing specific cohorts or size groups of oaks, leading to immediate changes in species composition, age structure, and growing space. Correspondingly, the reduced competition of overstory oaks can speed up the colonization of residual mid and understory maples. Exasperating this shift in forest composition is an underrepresented number of oak saplings or competitive oak seedlings with an overabundance of midstory maples (Fei and Steiner, 2007; Palus et al., 2018). Contemporary prescribed fires are often low-intensity, designed to minimize escape and impacts to air quality but often fail to increase understory light conditions for the promotion of oak advanced reproduction pools (Arthur et al., 2012). Further impacting the ability to achieve land management objectives for sustaining oak forests is that the ability to effectively intervene in maple colonization and expansion because they are already far outside their historical range of variation (Dey and Fan, 2009; Hutchinson et al., 2005). For example, unprecedented levels of red maple abundance has been reached in some parts of the eastern US when compared to other species (Fei and Steiner, 2007; Knott et al., 2019). Therefore, contemporary silvicultural treatments, including their 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 U.S., 44% of forest land is publicly owned of which 76% is administered by federal government entities (e.g., the Forest Service, National Park Service, etc.) and 21% is state-owned (Nelson et al., 2010). When it is the representative forest-type for a given site, these public forest landowners actively manage for the promotion of oaks, due to their ecological and economic importance. Silvicultural treatments include shelterwood cuts for regeneration harvests, prescribed burning to reduce competition and increase available light, and selection cuts. Due to limited resources in both capacity and capital, these treatments are typically implemented at small scales and for short durations, especially considering the size and long-term holdings of public lands. For instance, the Wayne National Forest in southern Ohio selectively cuts an average of 1.3% of their total land area per year. The average rotation in eastern US national forests is between 10 and 50 years with an average harvest area for national forests in the Appalachian ecoregion of ~ 9.9 ha over the past decade (US Forest Service, 2020). Thus, it remains to be tested whether current small-hectarage management operated at stand-levels can achieve objectives for oak-sustaining and maple-restraining in public forests and the surrounding region through time.

In this study, we examined a large, forested ecoregion in southern Ohio, which represents a temperate hardwood forest held by multiple ownerships, including large blocks of federal and state forest lands, and thousands of smaller private woodlands. We used a spatial-explicit, forest dynamic landscape model — LANDIS PRO to project changes in the top 26 abundant species over time under business-as-usual (BAU) and alternative silvicultural management, respectively. We aimed to address the following questions: 1) Can current public forest management 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 public lands have regional effects? 3) What are the relative contributions of NF and SF to sustaining oak and restraining maple at the regional scale?

## 2. Method and materials

### 2.1. Study area

Our study area is located in southeastern Ohio, north of the Appalachian Mountain range, covering approximately 2.1 million hectares of the Southern Unglaciated Allegheny Plateau ecological section (Fig. 1). The boundaries of the study area include 5 ecological subsections, namely, Ohio Valley Lowland (221Ec), East Hocking Plateau (221Ed), Unglaciated Muskingam Plains (221Ee), Western Hocking Plateau (221Ef), and Lower Scioto River Plateau (221Eg). This area has a humid continental climate, characterized by hot, humid summers and cool winters (Owenby and Ezell, 1992). The precipitation is evenly distributed throughout the year. The average annual precipitation and temperature range from 810 to 960 mm and from 10.2 to 12.8 ℃, respectively. The soils formed from the common lithologic types of sandstone, shale, siltstone, and limestone, and are mostly well-drained or moderately well-drained with fine, loamy textures (Pearcy et al., 1999). Forestland comprises 67% of the study area according to the 2011 National Land Cover Database and is dominated by broadleaf deciduous tree genera including oak (*Quercus* spp.), hickory (*Carya* spp.), maple (*Acer* spp.), and beech (*Fagus* spp.). Five percent of the study area is managed by the United States Department of Agriculture (USDA), Forest Service National Forest System (i.e., Wayne National Forest, WNF) while 7.5 % of the study area is managed by the Ohio Department of Natural Resources (ONDR). Similar to other public lands in the eastern US, these publicly-held forests are highly dissected by lands held by private landowners.

### 2.2. Modeling approach

We used a species-specific, forest landscape model, LANDIS PRO to simulate forest dynamics and landscape-scale disturbances. LANDIS PRO is a processed-based model that can simulate individual-species demography and stand dynamics within each grid cell while simulating landscape processes (e.g., seed dispersal, harvest, fire, and windthrow) as spatially contiguous events across the region (Wang et al., 2014). We used the LANDIS PRO model because it has been extensively calibrated with USDA Forest Service, Forest Inventory and Analysis (FIA) data (O'Connell et al., 2014) and applied to multiple ecoregions across the eastern United States (e.g., Brandt et al., 2014; Duan et al., 2022; Janowiak et al., 2018; Wang et al., 2019). We designed two scenarios, using contemporary datasets, to evaluate the effects of forest management for sustaining oak and restraining maple on public forests and at regional scales (including both public and private forest lands): (1) business-as-usual (BAU) scenario: all forest lands (both public and private) continue with current business-as-usual forest management practices; (2) alternative management (AltMgt) scenario: public lands are intensively managed while private lands continue to manage with business-as-usual practices.

### 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, but exceptions were made to include species with canopy potential and those that are important to forest structuring, or are of ecological or economic interest (Table 1). This approach accounted for 80% – 95% of the total basal area for each ecological section. We also included a pseudo species type to encompass all other species occurring on the landscape but that were not modeled at the species level.

Tree species' demographic processes (e.g., tree growth, maturity, sprouting, establishment, mortality, etc.) simulated in LANDIS PRO are driven by species-specific biological traits. We parameterized these species' biological traits (e.g., longevity, shade tolerance class, seedling dispersal distance, sprouting probability, etc.) based on previous studies

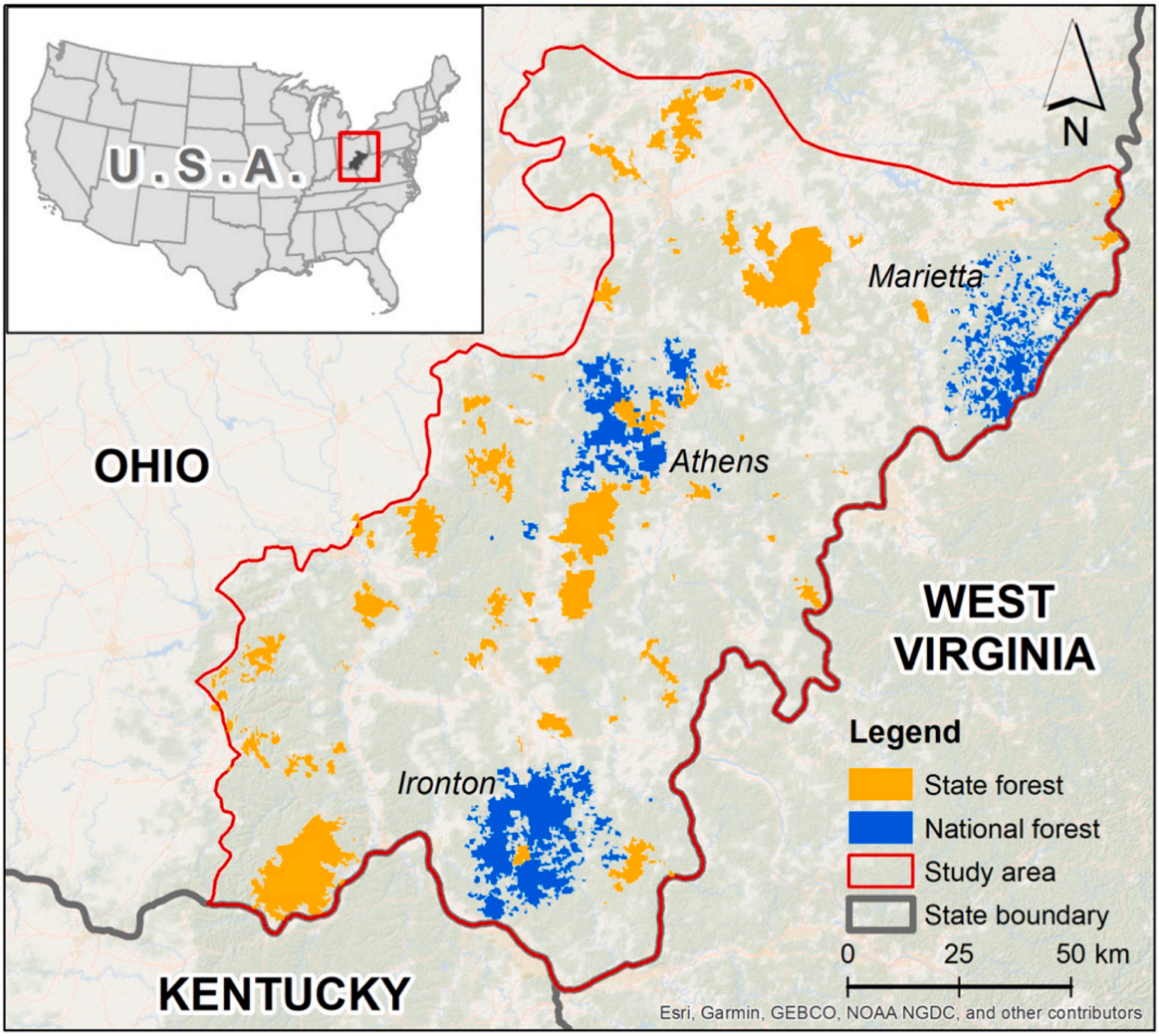


**Fig. 1.** Location of the study area (outlined in red). The colors indicate the Ohio Department of Natural Resources State Forest lands in orange and the Wayne National Forest in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Burns and Honkala, 1990; Wang et al., 2015). We used FIA data from 2000 to 2010 (FIA DataMart, 2020) and classified land cover data to develop a starting forest condition composition map for LANDIS PRO using Landscape Builder (Dijak, 2013). Each raster grid cell in the starting condition map contained species abundance by age cohort and initial land cover type configuration (Wang et al., 2014). We used the same initial forest condition for both management scenarios and simulated forest change from 2010 to 2160, using 10-year time steps at a 90-meter resolution. We ran 10 replications for each scenario to capture uncertainty resulting from stochasticity in the models. We used data from FIA and previous studies in old-growth forests from this study area (Goebel and Hix, 1996) to evaluate simulation results for the expected species basal areas, densities, and successional trajectories at the stand and regional scales based on Wang et al. (2014). All management parameters and scenarios were implemented in LANDIS PRO Harvest Module (Fraser et al., 2013). For BAU under different landownerships, we separately parameterized management on national forest land, state forest lands, and private lands to reflect the current management practices occurring over the last 10 years.

## 2.4. Business-as-usual (BAU) scenario

### 2.4.1. BAU silvicultural management on national forest (NF) land

We obtained the management records from the WNF during the period of 2010–2020 from the USDA Forest Service Timber Harvests database. Using these data, we combined the hectarages of very small treatments with the hectarages of larger treatments to reduce the number of individual activities we had to track to parameterize management in LANDIS. Eventually, we summarized the percentage of area silviculturally treated in each administration unit (Table 2) as the BAU scenario on NF. Overall, 1.6% of the WNF received the same type of silvicultural management over the 2010–2020 period.

### 2.4.2. BAU silvicultural management on state forest (SF) lands

Based on data from silvicultural practices that occurred from 2009 to 2015 on state forests from ODNR and an unpublished report, silvicultural practices included clearcuts, even- and uneven-aged regeneration cuts, totaling approximately 118,322 ha which is approximately 7.3% of the total area available for management (Table 3).

**Table 1**
Biological traits of individual tree species used in LANDIS PRO. Shade tolerance class 5 indicates the species is most shade-tolerant while 1 is least tolerant. Max Distance (m) is the species maximum seeding range distance in meters. Species have 95% chance of seeding within this distance. Effective Seedlings is the number of seedlings produced by each individual tree per year.

| Species | Scientific name | Average Longevity | Maturity Age | Shade Tolerance | Max Distance (m) | Sprouting Probability | Minimum Sprouting Age | Maximum Sprouting Age | Effective Seedlings |
|---|---|---|---|---|---|---|---|---|---|
| Red maple | *Acer rubrum* | 150 | 10 | 4 | 2160 | 0.9 | 10 | 100 | 30 |
| Sugar maple | *Acer saccharum* | 300 | 20 | 5 | 2160 | 0.8 | 20 | 80 | 30 |
| Silver maple | *Acer saccharinum* | 150 | 10 | 3 | 2160 | 0.8 | 10 | 80 | 50 |
| White oak | *Quercus alba* | 300 | 40 | 4 | 1080 | 0.7 | 10 | 100 | 60 |
| North red oak | *Quercus rubra* | 200 | 20 | 3 | 1080 | 0.7 | 10 | 120 | 20 |
| Black oak | *Quercus velutina* | 150 | 20 | 3 | 1080 | 0.6 | 10 | 100 | 20 |
| Chestnut oak | *Quercus prinus* | 300 | 40 | 4 | 1080 | 0.7 | 10 | 100 | 50 |
| Scarlet oak | *Quercus coccinea* | 80 | 20 | 2 | 1080 | 0.6 | 10 | 100 | 30 |
| Eastern hemlock | *Tsuga canadensis* | 300 | 20 | 5 | 2160 | 0 | 0 | 0 | 50 |
| American beech | *Fagus grandifolia* | 300 | 20 | 5 | 1080 | 0.8 | 10 | 100 | 20 |
| Blackgum | *Nyssa sylvatica* | 250 | 30 | 4 | 810 | 0.6 | 10 | 60 | 40 |
| Sourwood | *Oxydendrum arboreum* | 100 | 10 | 4 | 2160 | 0.7 | 10 | 80 | 20 |
| American basswood | *Tilia americana* | 200 | 20 | 3 | 1350 | 0.8 | 10 | 150 | 30 |
| Hickory group | *Carya* spp. | 250 | 30 | 3 | 1080 | 0.6 | 20 | 200 | 30 |
| Elm group | *Ulmus* spp. | 180 | 40 | 3 | 1620 | 0.7 | 10 | 60 | 30 |
| Yellow buckeye | *Aesculus octandra* | 200 | 20 | 3 | 1080 | 0.2 | 10 | 60 | 50 |
| Sycamore | *Platanus occidentalis* | 250 | 30 | 2 | 1080 | 0.4 | 10 | 100 | 50 |
| Black walnut | *Juglans nigra* | 200 | 10 | 2 | 810 | 0.6 | 10 | 150 | 50 |
| Black locust | *Robinia pseudoacacia* | 60 | 10 | 2 | 1080 | 0.7 | 10 | 50 | 20 |
| Sassafras | *Sassafras albidum* | 100 | 10 | 2 | 810 | 0.8 | 10 | 90 | 20 |
| Black cherry | *Prunus serotina* | 150 | 20 | 2 | 1080 | 0.8 | 20 | 100 | 30 |
| Bigtooth aspen | *Populus grandidentata* | 80 | 20 | 1 | 2160 | 0.5 | 20 | 80 | 35 |
| Yellow poplar | *Liriodendron tulipifera* | 200 | 20 | 2 | 2160 | 0.5 | 20 | 150 | 30 |
| Pitch pine | *Pinus rigida* | 200 | 20 | 2 | 1350 | 0.8 | 20 | 100 | 50 |
| Shortleaf pine | *Pinus echinata* | 150 | 20 | 2 | 1350 | 0.8 | 10 | 30 | 50 |
| Virginia pine | *Pinus virginiana* | 100 | 20 | 2 | 1350 | 0 | 0 | 0 | 50 |
| Pseudo spp. | | 150 | 30 | 2 | 1080 | 0.5 | 20 | 120 | 20 |

**Table 2**
BAU silvicultural management on Wayne National Forest (WNF).

| Management Area | Administration unit | Harvest method | Residual Basal Area ($m^2$ha) | Hectares treated per decade | Management area (ha) | Percent area treated per decade |
|---|---|---|---|---|---|---|
| Diverse Continuous Forest | Athens | Commercial Thin | 1.15 | 39.72 | 5273.28 | 0.8% |
| Diverse Continuous Forest | Athens | Single-tree Selection Cut | 2.3 | 62.25 | 4231.26 | 1.5% |
| Diverse Continuous Forest | Athens | Single-tree Selection Cut | 18.37 | 268.88 | 4231.26 | 6.4% |
| Forest and Shrubland Mosaic | Athens | Single-tree Selection Cut | 0 | 9.26 | 5113.78 | 0.2% |
| Historic Forest | Athens | Harvest Without Restocking | 0 | 1.98 | 3098.55 | 0.1% |
| River Corridor | Athens | Salvage Cut (intermediate treatment) | 0 | 0.37 | 457.46 | 0.1% |
| Forest and Shrubland Mosaic | Ironton | Commercial Thin | 20.66 | 24.54 | 8051.21 | 0.3% |
| Historic Forest | Ironton | Commercial Thin | 18.37 | 515.85 | 6924.17 | 7.5% |
| Historic Forest | Ironton | Commercial Thin | 20.66 | 54.46 | 6924.17 | 0.8% |
| Historic Forest w/OHV | Ironton | Commercial Thin | 13.77 | 110.29 | 5563.14 | 2.0% |
| Historic Forest w/OHV | Ironton | Single-tree Selection Cut | 13.77 | 312.96 | 5563.14 | 5.6% |
| Sardis Wetland | Ironton | Commercial Thin | 20.66 | 3.80 | 63.15 | 6.0% |
| Developed Recreation | Marietta | Commercial Thin | 20.66 | 4.24 | 221.85 | 1.9% |
| Diverse Continuous Forest | Marietta | Commercial Thin | 20.66 | 36.20 | 8051.21 | 0.5% |
| Forest and Shrubland Mosaic | Marietta | Commercial Thin | 20.66 | 79.51 | 6313.69 | 1.3% |
| River Corridor | Marietta | Stand Clearcut (with leave trees) | 2.3 | 5.34 | 3319.59 | 0.2% |

**Table 3**
BAU silvicultural management on State Forest (SF).

| Harvest method | Hectares treated per decade | Residual basal area ($m^2$/ha) | Residual description |
|---|---|---|---|
| Clearcut | 1537.00 | 0–0.92 | Some hickory trees left |
| Deferment / Two-aged | 1777.38 | 0.92–5.74 | Residual trees 25.4–55.88 cm of diameter at breast height (DBH), favor oak & hickory |
| Shelterwood-two-stage / First Entry | 1258.98 | 9.18–13.77 | Residual trees 35.56–50.96 cm of DBH, favor oak & hickory |
| Even-aged Thinning | 2784.64 | 16.07–25.25 | Thin from below resembles shelterwood, thin from above resembles uneven-aged. Roughly 2/3rds thin from above |
| Uneven-aged | 1052.59 | 16.07–25.25 | No understory treatment, removal of 25.4–76.2 cm of DBH |
| Uneven-aged w/ Groups | 215.29 | 13.77–18.37 | Same as above but includes groups (0.1–0.8 ha) semi-randomly located |

#### 2.4.3. BAU silvicultural management on private lands

We used the data from the FIA Ohio report (Widmann, 2016) and a geospatial disturbance database (i.e., LANDFIRE) to compile BAU silvicultural management on private lands. LANDFIRE raster data is information on forest disturbances interpreted from satellite imagery and represented over a 10-year period (LANDFIRE, 2018). We used LANDFIRE data to parameterize harvested area on private lands. We interpreted disturbance severity classes as 1) low severity, indicating forest thinning, 2) moderate severity, representing shelterwood harvests, and 3) high severity, as clearcut harvests. Most tree harvests were light and stands retained a large volume of residual trees. Based on estimates from Widmann (2016), there are approximately 143,460 ha of private lands treated per decade in our study area. LANDFIRE data estimated 38,022 ha treated by intensive harvests, and 1,105,438 ha treated by light harvesting (e.g., typically high grading or single tree selection). We further subdivided this information by ecological subsection (Table 4).

### 2.5. Alternative management (AltMgt) scenario

We designed and modeled a management scenario that included a greater degree of manipulative management on more hectares to sustain oak and restrain maples. The silvicultural practice used in the AltMgt scenario is a shelterwood method of regeneration, which has been widely adopted for building populations of large oak advance reproduction (Dey, 2014; Johnson et al., 2019). More specifically, the method involves a mid-story removal primarily targeted maples and other non-oak species to improve the number and vigor of oak advance reproduction and a subsequent overstory removal to regenerate the stand (Johnson et al., 2019). Based on the harvest history records in this region, we designed to implement the two-stage shelterwood with reserves. The first entry shelterwood entry aims to reduce the stand basal area to 11.48 $m^2$/ha, followed by a second entry that will further reduce it to 4.59 $m^2$/ha. After the second entry, we also implemented another round of thinning targets on red maple regardless of the age of the stand to reduce seed production and release treatments for oak regeneration. Starting in 2020 (i.e., the first iteration of the model simulation), each silvicultural treatment occurred at decadal intervals and treated 10% of public lands (i.e., including NF and SF) per decade, which is greater than the area currently treated (i.e., 1.6% on NF and 7.3% on SF). More detailed treatment parameters are listed in Table S1. We assumed private land management to remain as BAU and did not adjust the management approach under the AltMgt scenario.

**Table 4**
BAU silvicultural management on private lands, including treated hectares per decade (ha/decade) by silvicultural method.

| Subsection ID | Subsection name | Single tree selection | Thinning | Shelterwood | Clearcut |
|---|---|---|---|---|---|
| 221Ec | Ohio Valley Lowland | 1515.18 | 279.24 | 91.87 | 95.10 |
| 221Ed | East Hocking Plateau | 1791.18 | 290.57 | 124.65 | 136.79 |
| 221Ee | Unglaciated Muskingam Plain | 668.15 | 139.62 | 41.68 | 24.28 |
| 221Ef | Western Hocking Plateau | 4539.05 | 778.23 | 312.42 | 307.97 |
| 221Eg | Lower Scioto River Plateau | 3053.42 | 596.92 | 186.97 | 156.62 |

### 2.6. Data analysis

We simulated the two management scenarios for 150 years into the future and used species-level basal area and relative dominance as performance indicators. The basal area of a specific species was based on diameter at breast height (DBH) and tree density. Relative dominance was calculated as the species basal area divided by the total basal area of all species. We visualized management effects for each management scenario simulated through time by comparing plots of mean basal area and mean relative dominance for selected species. We represented the percentage of the landscape area by mean-DBH class to highlight differences in diameter distributions of trees among the two public landowner types (national forest and state forest) and the entire region (national forest, state forest, and private forest) as a measure of forest structure. We utilized the regional basal area of various oak species (including white oak, northern red oak, black oak, chestnut oak, and scarlet oak, collectively referred to as oaks) and maple species (including red maple, sugar maple, and silver maple, collectively referred to as maples) as the response variable and the basal area on NF and SF as the explanatory variable. The relative importance of NF, SF, and their interaction were estimated based on partial $R^2$ using the "relaimpo" package in R software (4.0.2).

## 3. Results

### 3.1. Effects of BAU and AltMgt on public forests

In public forests, species basal area and their relative dominance responded significantly different over time under the two management scenarios. For oaks and maples, under the BAU scenario, the total basal area of oaks showed a slight increase by 2050 and remained stable until 2110. However, beyond this point, it gradually declined until the end of the simulation. In contrast, the total basal area of maples experienced a dramatic increase, increasing from less than 4 $m^2$/ha to approximately 20 $m^2$/ha over the forecasted 150-year period (Fig. 2a, 2b). Maples accelerated in their share of total dominance during the 150-year simulation. By the end of 2160, maples, the vast majority being red maple, increased from less than 20% in 2010 to>50% of the total relative dominance. In comparison, oaks comprised 17.6% and 12.3% of the total relative dominance on NF and SF in 2160, respectively (Fig. 2d, 2e). Under the AltMgt scenario, the basal area of oaks on public forests increased to over 12 $m^2$/ha and fluctuated around this value until 2160 (Fig. 2g, 2 h), occupying about 30% of total relative dominance (Fig. 2j, 2 k). Further, maples under the AltMgt scenario, increased to > 9 $m^2$/ha, with their basal area remaining within this level (Fig. 2g, 2 h) and relative dominance between 20% and 33% (Fig. 2j, 2 k).

Shade-intolerant species, such as bigtooth aspen, yellow poplar, and black locust, among others, experienced a reduction of about half of

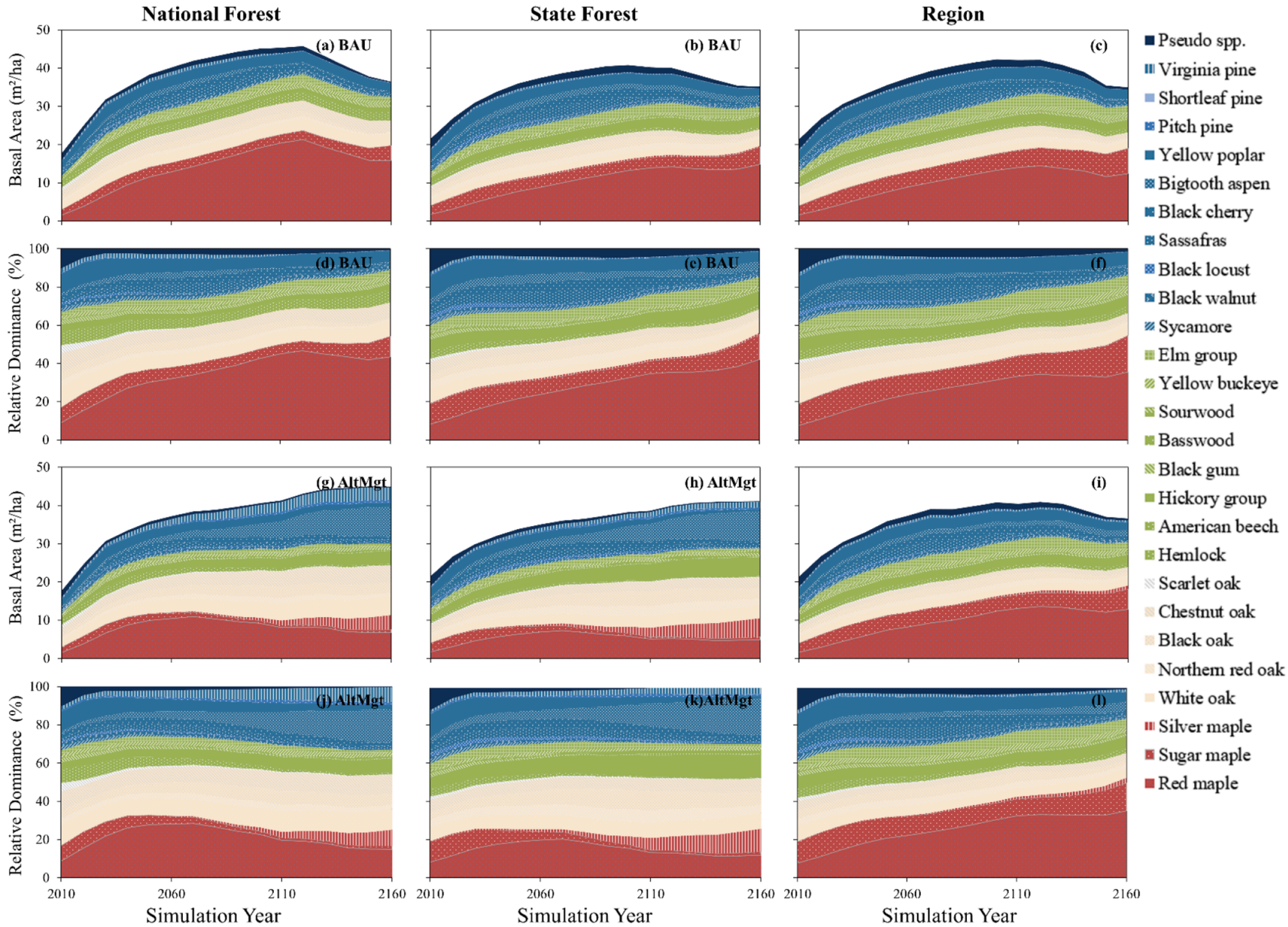


**Fig. 2.** The basal area and relative dominance of 27 species under the business as usual (BAU) scenario in the first two rows and alternative management (AltMgt) scenario in the last two rows. The region includes all the public lands and private lands, and the private land management remains as BAU and did not adjust the management approach under the AltMgt scenario. Oaks are in creamy white, and maples are in red. 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 colour in this figure legend, the reader is referred to the web version of this article.)

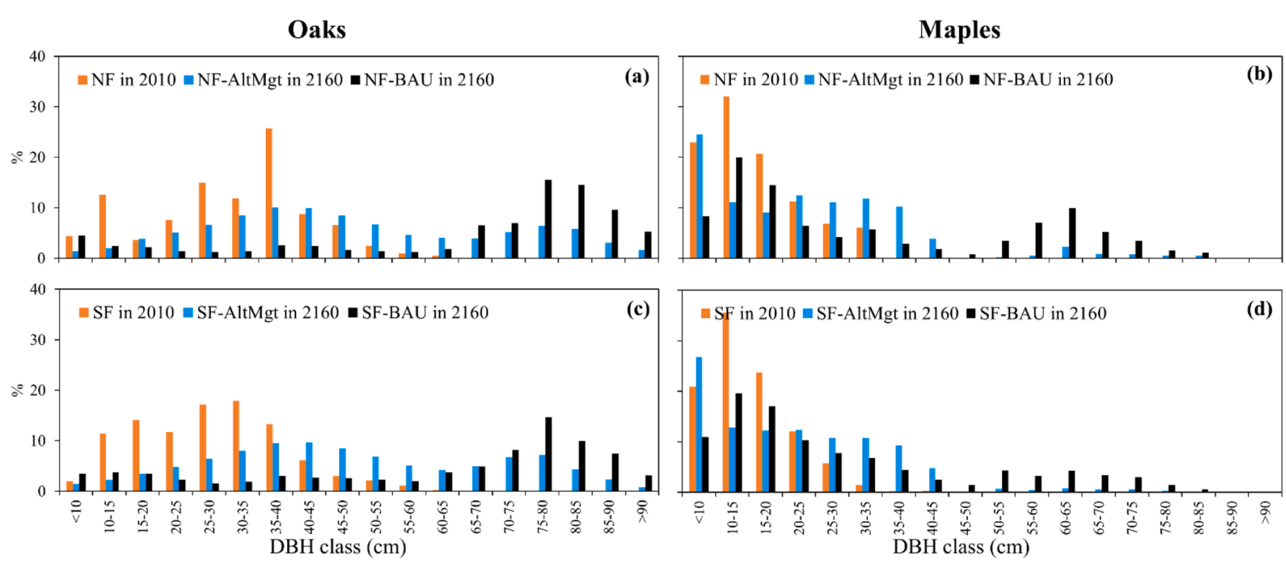


**Fig. 3.** Comparison of DBH distributions for (a) NF oak, (b) NF maple, (c) SF oak, (d) SF maple 2010 and 2160 under business as usual (BAU) and alternative management (AltMgt) scenarios. The x-axis is the DBH class, and the y-axis is the average percentage of the forest stands in each diameter class.

their total basal area under the BAU scenario (Fig. 2a, 2b). Conversely, under the AltMgt scenario, these species expanded their basal areas to 1–15 times their initial values (Fig. 2g, 2 h). Under the BAU scenario, shade-tolerant species (e.g., elms, hickories, beech, hemlock, etc.) were suppressed by more competitive maples, occupying ~ 17% of total dominance in 2160 (Fig. 2d, 2e). Under the AltMgt scenario, shade-tolerant species represented 13–18% of the relative dominance (Fig. 2j, 2 k).

There was a large shift in the distribution of mean diameters of oaks and maples to larger diameter classes from 2010 to 2160 under both scenarios. In 2010, most oaks occurred between the 25–40 cm DBH classes. Due to the low levels of active management occurring across public lands under the modeled BAU scenario, oaks grew and occupied high abundances in the over 70 cm DBH classes (Fig. 3a, 3c). In contrast, the AltMgt scenario spread the diameter of oaks across the entire distribution over the 150-year period (Fig. 3a, 3c). Additionally, the reverse-J DBH distribution maples in 2010 shifted to a right-skewed bell-shaped distribution under the BAU scenario, while the distribution retained its reverse-J shape and centered on relatively small DBH classes under the AltMgt scenario (Fig. 3b, 3d).

### 3.2. Effects of BAU and AltMgt regionally

At the regional scale, total basal area of all species (Fig. 2c, 2i) and relative dominance (Fig. 2f, 2 l) had similar patterns under the two scenarios. Under the BAU scenario, 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 11.6% dominance in 2160 after 150 years of contemporary low management levels. Maples expanded immensely during this period, from 4.1 $m^2$/ha to 19.15 $m^2$/ha with 54.8% of relative dominance at the end of the simulation (Fig. 2c, 2f). The basal area of early successional species such as yellow poplar, bigtooth aspen, etc. decreased from 5.3 $m^2$/ha with 24.8% dominance to 4.2 $m^2$/ha with 12.1% dominance by 2160. Basal area peaked in 2100 with 42.3 $m^2$/ha under the BAU scenario and 40.8 $m^2$/ha under the AltMgt scenario (Fig. 2c, 2i).

Regionally, the diameters of oaks were concentrated around > 70 cm DBH class after 150 years of BAU; however, they were more evenly distributed under the AltMgt scenario, especially in small and medium diameter classes (i.e., 10–60 cm) (Fig. 4a). The DBH distributions of maples under two scenarios have similar patterns when summarized regionally–the diameters of maples were clustered around 10–15 cm DBH class in 2010 and grew to the 50–60 cm DBH class after 150 years of BAU management (Fig. 4b). The results indicate that more intensive management (i.e., AltMgt) on public lands has limited regional effects on restraining maples.

### 3.3. Relative contribution of NF and SF management regionally

The relative contribution of NF and SF management on the structure and composition of oaks and maples fluctuated regionally throughout the 150-year simulation. Under the BAU scenario, NF contribution to oak basal area ranged from 16% to 44%, while the contribution from SFs ranged from 26% to 49% (Fig. 5a). The NF and SFs combined contribution to maple basal area exceeded > 85% in some years but was also as low as 43% (Fig. 5b). Under the AltMgt scenario, the contribution of the NF to oak basal area peaked in 2100 (Fig. 5c), while maple basal area declined (Fig. 5d). Overall, our results indicate management implemented on the NF and SFs is important for explaining regional changes in oak-maple dynamics when private lands maintain BAU management. Also, the NF and SFs' relative contributions to the dominance of oak and maple regionally are not constant over time.

## 4. Discussion

This study attempts to assess the long-term effects and contribution of public forest management for sustaining oak and restraining maple across landownerships, through time, and at regional scales. We simulated forest successional changes with active forest management across a forest landscape using real data, initiating our models in 2010 at 90 m resolutions, and projected forest conditions forward 150 years into the

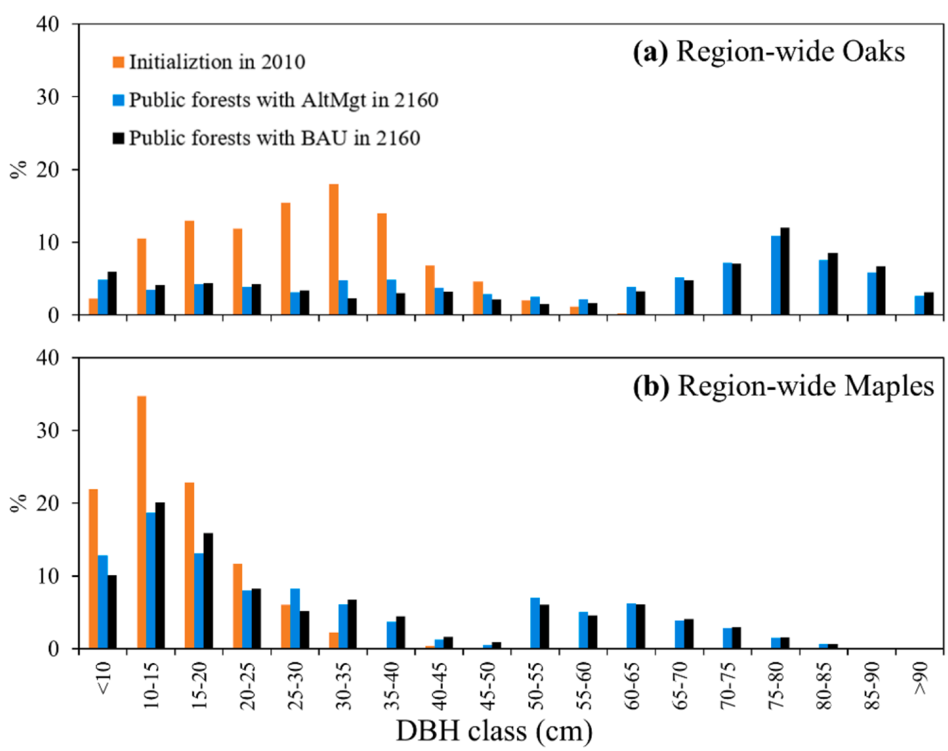


**Fig. 4.** Comparison of region-wide (a) oak and (b) maple DBH distributions in 2010 and 2160 under business as usual (BAU) and alternative management (AltMgt) scenarios. The x-axis is the DBH class, and the y-axis is the percentage of the forest stands in each diameter class.

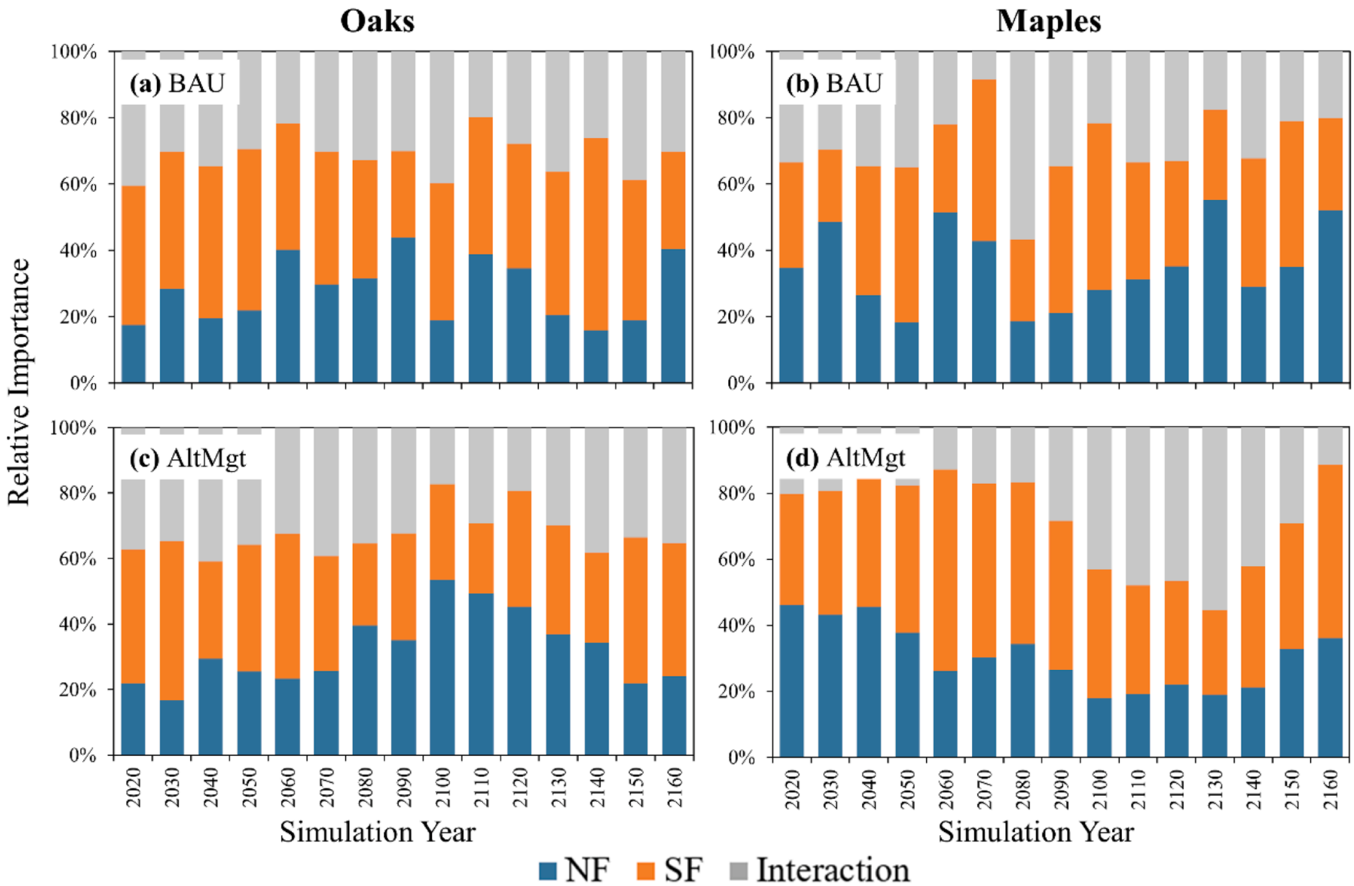


**Fig. 5.** Relative contribution of the national forest (NF), state forests (SF), and their interactions (i.e., interactive effects of NF and SF) through time on regional oak (a, c) and maple (b, d) basal area under business-as-usual (BAU) and alternative management (AltMgt) scenarios.

future using a spatially explicit and dynamic forest landscape model. Using this approach, we compared outcomes for oak and maples based on two modeled forest management scenarios, a business-as-usual approach on all lands and an alternative approach on public forests that treated more acreage, more often. This factorial simulation experiment allows us to disentangle and quantify the relative contribution of national and state forests in achieving management objectives for sustaining oak forests in the eastern US. Based on our study, increasing the pace and scale of active forest management, will sustain oaks across diameter distributions while minimizing increases in large, dominant maples. Our model results suggest that under current management practices, maples will more than double in abundance on public lands. Further, when considered regionally, management on public forests is an important driver in oak-maple dynamics locally but is unable to dramatically shift species successional processes across the landscape when private landowners continue with contemporary management practices.

Our results show that BAU management implemented in the public forests may not successfully sustain oak, but instead, favors the continued colonization of maple through time, contradicting public land management objectives. Unfortunately, a large proportion of oak forests in the eastern US have had nearly a century of minimal or no management causing them to depart from their historical range of variation (Hanberry et al., 2020; Nowacki and Abrams, 2008). Contemporary midstory composition of oak forests in the eastern US is comprised of overly abundant mesophytic species (i.e., red maple, sugar maple), suggesting a lack of canopy replacement by ecologically and economically important oaks with forest succession. Our results suggest that BAU increases competition intensity to oaks in the under- and midstory while promoting the proliferation of mesophytic species over the long-term. Specifically, in areas that are untreated, increases shade-tolerant species such as maple (*Acer* spp.) and American beech (*Fagus grandifolia*) in midstory layers result in a substantial reduction in understory light, further allowing shade-tolerant mesophytes to self-perpetuate, hindering oak seedlings' growth (Brose et al., 2008). Business-as- usual management practices such as commercial thinning, single-tree selection encourage more opportunistic species expansion and boost the intensity understory competition to oak saplings (Nowacki and Abrams, 2008). As a result, oaks in our study, are largely absent from sapling and midstory size classes, even though mature overstory oaks (e.g., DBH ≥ 40 cm) continue to grow. These results (Figs. 3, 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 under more intensive management (AltMgt), management objectives for oak on public forests could be achieved by altering species composition and diversifying size-class structure. Compared to the BAU silvicultural prescription, the alternative management scenario included multi-entry shelterwood harvests and standalone harvest targeting red maple, leading to relatively stable oak and maple levels throughout the 150-year simulation. For example, the dominance of oak and maple was about 20–35%, respectively, and neither species group declined below 10% nor increased above 50% as they did under the BAU scenario (Fig. 2). These results indicate that the AltMgt silvicultural approach was effective to meet structural and compositional objectives for oak forests in this region. This approach also resulted in a greater establishment of fast-growing, shade-intolerant species such as bigtooth aspen (Fig. 2), even though they were eventually suppressed by oaks and maples (Iverson et al., 2008; Swaim et al., 2018). In addition to affecting species composition, the AltMgt approach resulted in greater proportions of oak in smaller size classes and higher size class diversity (Figs. 3, 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 more intensive management in public forests had limited impacts at the regional scale. The public forests treated by alternative management practices only comprised a small proportion (i.e., ~8%) of the forested cover in our study area. The local-scale impacts introduced by stand-level alternative management were moderate at the regional scale. For example, region-wide maples and oaks shifted to over 50% and less than 14% of total dominance respectively under the AltMgt scenario (Fig. 2); a pattern that was not significantly different from the BAU scenario. This result also reveals that contemporary management of privately owned forests plays an important role in regional oak maintenance and requires further evaluation.

The management of public forests can help in explaining regional changes in oaks and maples when private land management continued its BAU management. Public forest contribution to regional forest composition and structure is not constant but changes over time (Fig. 5). These divergences were caused by differences in the underlying forest ecology and structure of the NF and SF (Palus et al., 2018). Generally, the forest area managed by SF is larger than NF, and the average DBH of oak is smaller on SF (Fig. 3a, 3c). The alternative management scenario may therefore, result in proportionally more oaks on SF in an early succession stage of development, causing more variation in oak basal area during the first few decades of the simulation. As a result, SF is more important than NF in sustaining oak early in the simulation. On the other hand, NF reached the climax after a 90-year simulation since the aging of overstory oaks resulted in major changes to oak basal area (Fig. 5c). This implies the need to have different priorities and time frames in mind when developing long-term conservation plans for oaks and allocating resources in the most cost-effective way to ensure their sustainability.

Forest managers and researchers encounter limitations when they try to use controlled field experiments to address questions regarding management alternatives and their cumulative effects over large spatial extents (e.g., $>10^4$ ha) and long-time spans (e.g., >50 years) (He, 2008). The effects of alternative management options are long-lasting and may take decades to be comprehensively evaluated. For example, the shelterwood method in our alternative management scenario is widely recommended to promote oak advance reproduction (Johnson et al., 2019; Schlesinger et al., 1993). However, it can take 10 to 50 years to develop sufficient numbers of large oak advance reproduction using this method (Sander, 1972). This time span is often beyond the capacity of short-term field studies or observations. Additionally, the implementation of alternative management for oak requires long-term commitments. The shift in management priorities, reduced budgets, and transfer of professional workforce may disrupt the established practices for sustaining oaks, potentially resulting in the failure of the entire management process (Dey, 2014). These challenges could also impede the adoption of alternative management strategies.

Forest landscape modeling approaches are important tools to compensate for the limitation of field experiments as they can represent an effective means to disentangle and quantify compounding impacts (e.g., from management, disturbances) throughout time at stand- to regional-scale via multiple scenarios designs with much fewer costs (Duan et al., 2021; Gustafson et al., 2020). In this study, we demonstrated that by using a forest landscape modeling approach, we can examine the effects of different silvicultural alternatives for achieving desired management goals over large continuous spatial scales (i.e., including public and private lands) and longtime spans (i.e., 150 years) that would have otherwise been difficult to intuitively test or understand.

## CRediT authorship contribution statement

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

## 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.foreco.2023.121331.

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