



## Review and synthesis

## Silvicultural options for open forest management in eastern North America

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## ABSTRACT

Fire-sustained open oak and pine forests were once widespread across eastern North America, but are now comparatively scarce. To regain the goods and services of these open forests, managers are increasingly looking to restore them with the silvicultural systems and tools best suited to meet their objectives. Hence, we synthesized a number of research efforts and case studies from open pine, mixedwood, and oak-dominated forests in eastern North America to demonstrate the silvicultural options available and recognized knowledge gaps. The silvicultural treatment options and tools available are very similar to those applied in closed-canopy forests, even if the objectives are fundamentally different. For instance, while conventional practices in naturally regenerated forests concentrate on managing closed tree canopies to increase periodic yields and encourage new tree recruitment, open forest silviculture focuses on the maintenance of a vertically simple and understocked canopy to facilitate a robust herbaceous groundflora and limit woody plant regeneration. To achieve and sustain this understocked condition, open forest management applies multiple tools (e.g., prescribed fire, periodic harvests or deadenings, and herbicide use and planting if and when needed) along with other understory enhancement and maintenance treatments. This review demonstrates that while we have learned much about open forest silviculture over the decades, many information gaps and challenges for managers remain.

## 1. Introduction

Silviculture is the practice of controlling the establishment, density, composition, growth, quality, and reproduction to meet resource objectives and achieve management outcomes for a given forest (e.g., Smith et al., 1997). Through the regulation of the stand's biological and ecological processes, silviculturists intervene to create and maintain a set of desired conditions consistent with any of a number of management objectives. Although optimizing wood yield has often been the primary (and, in many cases, the only) management objective (Caputo, 2012; Batavia and Nelson, 2016), silvicultural systems can be—and are—designed to produce other outcomes. This is reflected in the growing movement to restore and maintain open forests to parts of eastern North America (e.g., Greene et al., 2016; Dey et al., 2017; Matusick et al., 2020). Indeed, for many oak- and pine-dominated ecosystems, open forests are the preferred framework for public land management (e.g., Masters et al., 2003; Hedrick et al., 2007; Lorber et al., 2018).

Open forests (from sparsely treed savannas to denser woodlands,

spanning from 10% to 75% of full stocking) are typically comprised of fire-tolerant overstory species (such as oaks and pines) over an herbaceous understory and sparse (often absent) woody midstory (Hanberry et al., 2018). In eastern North America, widespread forest management, fire suppression, overuse, neglect, and densification following other land use changes have resulted in the conversion of these previously common open ecosystems to closed-canopy forests that are structurally and functionally different (Hanberry et al., 2018; Hanberry et al., 2020). The losses of open forests come at considerable ecological cost, as they have contributed to sharp and widespread declines of many once-abundant birds (Rosenberg et al., 2019), small mammals (Ingersoll et al., 2013; Hammerson et al., 2017), terrestrial insects (Koh et al., 2016; van Klink et al., 2020), and even prominent tree species such as longleaf pine (*Pinus palustris*), shortleaf pine (*Pinus echinata*), and white oak (*Quercus alba*) (Jose et al., 2006; Fei et al., 2011; Anderson et al., 2016).

By quickly halting—or even reversing—the loss of open forests and concurrent declines in associated species, silviculturists can help retain sufficiently robust populations so as to avoid the curtailment of

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seemingly unrelated practices (e.g., limiting timber harvests in the summer ranges of colony-hibernating bats affected by white-nose syndrome or those lost to wind turbines while migrating; Drake et al., 2020). Fortunately, treatments to restore and maintain open forests for conservation purposes are just as feasible as those that promote timber production and can involve the same types of interventions. As an example, variable retention harvesting has been developed to help produce overstory complexity in closed forests (Gustafsson et al., 2012; Stanturf et al., 2014b) and could be adapted for open forests if some of the characteristic large-diameter, fire-tolerant trees are permanently retained for their structural and compositional contributions over a persistent and appropriate groundflora. Such retention would be a notable difference from other partial harvesting treatments (such as shelterwoods or multiple/deferment cuttings), for which harvest decisions are made to eventually encourage reestablishment of a fully stocked stand of trees. Variable retention forestry is also capable of retaining other biological legacies, such as large snags and downed dead wood, and typically encourages spatial heterogeneity of legacy features, thereby adding even more complexity to the restored environment (Gustafsson et al., 2012; Stanturf et al., 2014b).

While a logical extension or adaptation of existing silvicultural practices, the management of open forests presents a series of unique challenges to silviculturists. Further, guidance for the most effective silvicultural tools to restore open forests has lagged behind implementation, with the translation of available knowledge into practical treatment options limited to a few prominent covertypes (e.g., longleaf pine). However, new opportunities for the implementation of silviculture to develop and maintain open forest ecosystems will continue to arise, especially in the large portions of eastern North America (particularly oak-dominated landscapes) that lack consistent, organized management because of poor timber markets or limited guidance. Hence, in this paper, we will 1) briefly review objectives and characteristics of conventional silvicultural systems; 2) provide a silviculture-based context for open forests through a survey of the existing literature of these ecosystems; 3) differentiate between management objectives for closed and open forests; 4) develop some key lessons using a number of case studies of open forest restorations; and 5) suggest ways open forest management could be improved (including identifying research needs).

## 2. The uniqueness of open forest management

The primary distinctions between more conventional forest management practices in eastern North America and open forest silviculture lies in what motivates their use and what are considered successful outcomes. To recognize these inherent and fundamental differences, a common understanding of the history, structure, composition, and dynamics of the open forests of eastern North America is needed (see Hanberry et al. (2018) and Hanberry et al. (2020) for more detailed accounts). Many of the now-widespread closed forests of this region developed from open forests well after Euro-American settlement (Hanberry and Abrams, 2018; Hanberry et al., 2018). Most forests tend to quickly densify, develop a closed-canopy, and experience self-thinning until a major disturbance resets succession and an eventual return to canopy closure (Hanberry et al., 2020). In general, conventional silvicultural practices result in tree domination in all strata (Smith et al., 1997; Puettmann et al., 2009), rather than coexistence of sparse trees with an abundant herbaceous layer (Hanberry et al., 2018). When coupled with various types of stem density management, the predominant driver of forest dynamics in much of eastern North America has become stand establishment and harvesting (Pan et al., 2011).

Historically, open forests were stable ecosystems characterized by a generally simple vertical canopy structure consisting of a sparse to moderately treed overstory of relatively low taxonomic diversity, a limited midstory, and an abundant and diverse herbaceous groundflora dominated by grasses and/or forbs, which through a variety of feedback

loops also helped limit the dominance of trees and other woody plants. As an example, in open forests where C<sub>4</sub> bunchgrasses are abundant, tree seedling establishment is constrained by competition for soil moisture (e.g., Davis et al., 1999); these C<sub>4</sub> bunchgrasses also provide a continuous, highly flammable fuel which promotes the surface fires capable of retarding shrub and tree dominance (Fill et al., 2016).

Perhaps the archetypal example of open forests were the once widespread longleaf pine communities of the Atlantic and Gulf Coastal Plains, predominantly maintained by frequent surface fires (fire return interval (FRI) of 1–3 years), many of them human-set (Frost, 2006; Kirkman et al., 2018). Open forests were also found in most ecosystems that experienced frequent surface fires (as opposed to periodic catastrophic fires), including shortleaf pine in the Upper Coastal Plain and Interior Highland regions, the red (*Pinus resinosa*) and jack (*Pinus banksiana*) pine “barrens” in the northern Lake States, the oak-dominated (primarily white, but also post (*Quercus stellata*) or burr (*Quercus macrocarpa*) oaks) woodlands and savannas of the Central Hardwoods region (e.g., Hanberry et al., 2014b; Galgamuwa et al., 2019; Hanberry et al., 2019), and other more localized oak “openings” and “barrens” in various parts of the Midwest and Northeast (Radeloff et al., 2000; Anderson et al. 2007; Considine et al., 2013, Bassett et al., 2020). Decades to centuries of alterations to the disturbance regimes, changing silvicultural practices, and land-use history of these varied open forest communities all play a major role in why silviculture options and treatments to sustain them need to be considered differently.

### 2.1. The primacy of groundflora management in open forests

Assessments of past literature and the few remaining examples of frequently burned open forests clearly show groundflora characterized by a perennial herbaceous component (grasses and forbs) that is robust (high cover/abundance) and diverse in both oak (Leach and Givnish, 1999; Peterson and Reich, 2008; Considine et al., 2013) and pine ecosystems (e.g., Kirkman et al., 2001). In more open pine and oak savannas (e.g., canopy less than 40%), warm season C<sub>4</sub> bunchgrasses, such as wiregrass (*Aristida stricta*), and bluestem grasses (*Andropogon* spp., *Schizachyrium* spp.) often dominate. Where C<sub>4</sub> grasses do not dominate, cool-season C<sub>3</sub> grasses (e.g., *Panicum* spp.) and sedges may be abundant, particularly in more shaded and/or mesic conditions. Pastoralists once took advantage of this abundant herbaceous groundflora in the open forests across eastern North America. Tillotson and Greeley (1927, p. 12) estimated that at least 75% of the woods in their central hardwood region were “heavily pastured” and as late as the 1930s, most of the nearly 81 million hectares of southeastern US forests were classified as being capable of supporting livestock grazing (Wahlenberg and Gemmer, 1936). In doing so, livestock filled at least part of the grazing and browsing role of large ungulates and rodents that helped maintain low tree densities and a rich groundflora in open forests.

Some have suggested that early successional forests (the “preforest” stage of Franklin et al. (2018)) are the key missing element from contemporary landscapes dominated by closed forests (e.g., Swanson et al., 2011), but we disagree with this characterization. Early successional forests share some—but not all—attributes of open forests, including their high diversity of non-tree species and a rich, ruderal-dominated herb layer (e.g., Hansen et al., 1991; Swanson et al., 2011; Franklin et al., 2018; Hanberry et al., 2018). However, by definition early successional forests are ephemeral (transitionally dynamic) while open forests are structurally and compositionally stable (Hanberry et al., 2018; Hanberry et al., 2020). Once canopy closure occurs in early successional forests, light-demanding groundflora and their dependent organisms decline (Schlossberg, 2009). In contrast, open forests continually sustain both ruderal and many non-ruderal species, some of high conservation value (Walker and Peet, 1984; Drew et al., 1998; Brewer and Vankat, 2006; Jose et al., 2006). Open forests also have a partial overstory (varying from widely spaced to moderately (or patchily) stocked), typically of fire-tolerant tree species that may be old,

uneven-aged, and self-replacing (Hanberry et al., 2018); early successional stands rarely have such an age-class structure and replacement dynamic. Given high rates of plant endemism in many open forests and potentially scores or even hundreds of species of conservation concern in their groundflora (some with limited capacities to recolonize a shifting mosaic of early successional stands), restoration of a more permanent and stable open environment should be preferred (Hanberry et al., 2020).

## 2.2. Frequent surface fires are vital to the maintenance of open forests

Numerous accounts (e.g., Denevan, 1992; Harper, 1998; Williams, 2005) mention the frequent and often large-scale use of fire by the early inhabitants of eastern North America; this widespread disturbance undoubtedly shaped the region's vegetation patterns in many lasting ways. For instance, the dominance of fire-tolerant (rather than shade-tolerant) oaks and pines in the sparse overstory of open forests suggests the critical role of frequent surface fires (Hanberry, 2019). In oak savannas and mesic longleaf pine sites, observed patterns of groundflora and fungal community diversity and abundance are strongly related to fire frequency (Peterson et al., 2007; Peterson and Reich, 2008; Walker and Peet, 1984; Kirkman et al., 2001; Semenova-Nelsen et al., 2019). Given that major changes in groundflora composition can occur even during a relatively short period (< 20 years, often much less) of fire exclusion (e.g., Anderson et al., 2000), it is not surprising that managing burn frequency and its impacts on groundflora is foundational to open forest silviculture.

This influence is exerted through multiple processes. In addition to killing fire-sensitive plants, frequent fire limits the accumulation of litter and duff on the forest floor. This is particularly important in open longleaf pine, where these fuels accumulate rapidly in the absence of fire (Hendricks et al., 2002; Hiers et al., 2007; Veldman et al., 2014). Less is known about the importance of duff to the groundflora in open oak forests, where it does not tend to accumulate. Litter and duff accumulation may prevent the emergence of perennials and the establishment of new plants by creating a mechanical barrier and limiting light penetration, a germination requirement for some species (Vasquez-Yanes et al., 1990); chemicals such as tannins in accumulated litter can also retard groundflora establishment. Fuel-derived hot-spots on the forest floor can have both detrimental effects by killing seeds or reducing their germination, and positive ones by limiting competitors of desired species (Dell et al., 2017). Fire can also prove vital to open forest groundflora because some species require smoke exposure or heat-mediated seed scarification to germinate (Lindon and Menges, 2008; Luna et al., 2009).

Fire season effects on the groundflora have been examined most closely in longleaf pine communities, as summer lightning fires were common historically. For some species, growing season burns result in more synchronized flowering, which could benefit reproductive success (Platt et al., 1988). However, for a suite of common legumes, the effects of fire season on flowering and fruiting led Hiers et al. (2000) to conclude that variation in when fires occur may ultimately benefit the greatest number of groundflora species. Much less is known about the effects of fire season on the groundflora in oak and oak-pine woodland systems, where historic fire regimes were dominated by dormant-season anthropogenic fires (Guyette et al., 2002; Lafon et al., 2017). However, some evidence does suggest that repeated growing season burns can favor fire-tolerant pine, oak, and hickory regeneration by causing greater mortality to mesophytic hardwoods (e.g., Boyer, 1990; Brose et al., 1998).

## 2.3. Land-use history and open forest groundflora

Land-use history is also an important and often confounding driver of the current groundflora in open forest systems, as it can influence the presence of a native seed bank. Although recent fire history may be

more important, longleaf pine stands with an agricultural history (row crops or improved pastures) tend to have a lower groundflora richness than continually forested sites with their more intact seed banks (Veldman et al., 2014). When light-demanding herbaceous plants are mostly absent, the groundflora potential of a site depends on a buried seed bank (Cohen et al., 2004). Although hard-seeded species (e.g., legumes) can form long-term persistent seedbanks (longevity > 5 years to decades), seeds of many species are short-term persistent (1 to 5 years longevity) to transient (< 1 year, common in grasses), and thus unlikely to be present in the seed bank (Kaesler and Kirkman, 2012).

## 3. Silvicultural tools and options for open forests

Open forest silviculture employs most of the same concepts, tools, and methods as used in closed forests, however the application, timing, and purpose of the treatments will likely differ considerably. As previously noted, open forest management does not focus on initiating widespread tree regeneration to create a well-stocked stand that optimally utilizes growing space. Instead, open forests focus on maintaining a high level of native groundflora diversity, with only enough regeneration to periodically and gradually replace a limited number of overstory trees. This is true regardless of forest type, from oak savannas and mixedwood woodlands in the central US to the southern pine-dominated open forests of the South. To date, the primary motivation for open forest management has been driven by wildlife needs (especially for declining, threatened, or endangered species), such as the red-cockaded woodpecker (RCW; *Picoides borealis*), a territorial, non-migratory cooperative breeding bird dependent on the once-common, open pineywoods of the southern United States (Conner et al., 2001; Anderson et al., 2016; Smith et al., 2018). In the case of RCW, overstory reductions and prescribed fire have driven management actions to help recover this bird by maintaining a preferred groundflora and limiting the woody midstory (e.g., Stephens et al., 2019). Managers across the Central Hardwoods region have likewise engaged in open forest restoration to improve habitat conditions for a large number of wildlife species, from bats to pollinators to migratory songbirds (e.g., Barrioz et al., 2013; Cox et al., 2016; Hanula et al., 2016).

### 3.1. Prescribed fire as an essential tool

As can be seen in the aforementioned case of RCW habitat, prescribed fire is considered an essential tool for open forest silviculture because of how it influences vegetation and other environmental attributes. To use fire successfully, one must first identify the needed burning regime to achieve the desired outcomes. This regime includes functional knowledge of the ecology of the fuels (sensu O'Brien et al., 2008; Mitchell et al., 2009b) and specific traits such as fuel composition and accumulation rates, season of burn, intensity of burn, and effective fire return interval. Today, these may differ from those experienced historically, particularly given changes to fuels, types, timings, and frequency of ignitions, and land use patterns. Managers must also carefully implement prescribed fire to meet specific objectives that may vary over time. For instance, even the most fire-tolerant pines and oaks can be susceptible to fire-related mortality when young, so silviculturists should consider withholding burns during critical tree recruitment stages (e.g., Dey et al., 2017). Prescribed fire may also be unavailable to some because of smoke management issues, diminished number of burn days, unacceptable risk of fire escapes, or dangerous fuel conditions; others have avoided burning because of significant risk of wood quality degradation from bole injury and related decay (Mann et al., 2020). Ultimately, managers need to balance what is desirable with what is possible. As an example, on some mesic sites already occupied by fire-sensitive species—especially those capable of vigorous resprouting following top-kill—the requisite fire intensity to control these competitors may not be practicable and limited resources may be

better expended on less affected sites (Matlack, 2013).

While long considered as a useful option to reduce fire-sensitive tree species and limit their competition with desired taxa (e.g., Boyer, 1990; Brose et al., 1998), prescribed burning can also support the genetic integrity of shortleaf pine (which can sprout when top-killed as a seedling) by filtering out fire-sensitive hybrids with non-sprouting loblolly pine (*Pinus taeda*) (Tauer et al., 2012). Hiers et al. (2007) posited that high intensity fires that topkill or kill larger midstory stems are not necessary in xeric longleaf pine systems because it is forest floor reduction, which can be obtained with frequent low-intensity burns, that drives groundflora diversity. Prescribed fire in oak woodlands and forests tends to significantly increase groundflora richness, as new plants establish from the seed bank (Hutchinson et al., 2005; Maginel et al., 2019). In longleaf pine landscape mosaics where former agriculture sites are connected to remnant sites, the groundflora of old fields may recover to a substantial degree with frequent fire, although a subset of dispersal-limited species are likely to be absent (Kirkman et al., 2004). However, note that prescribed fire alone—even when applied repeatedly—may yield only a modest groundflora response if the tree canopy remains mostly closed (Hutchinson et al., 2005; Bassett et al., 2020). Research also suggests that prescribed fire does not always produce equal levels of understory improvement. In topographically diverse landscapes such as the Missouri Ozarks, groundflora on exposed xeric sites responded more to burning than on protected mesic sites, even though large-scale fire effects on stand density were similar (Maginel et al., 2019).

Fire frequency also plays a crucial role. In long-term studies that have examined groundflora response to a range of fire frequencies, more burns typically resulted in the greatest levels of species richness and/or the abundance of herbaceous plants (e.g., Knapp et al., 2015a). Glitzenstein et al. (2003) reported that long-term annual or biennial burning resulted in robust groundflora communities in South Carolina and Florida longleaf pine sites. Similarly, Brockway and Lewis (1997) found that biennial winter burns in some longleaf pine ecosystems resulted in the greatest levels of species richness and abundance of herbaceous plants over four decades of treatment. Similarly, in an oak savanna landscape biennial fires conducted over 30 years limited woody understory coverage while producing the most species-rich and herb-dominated groundflora (Peterson et al., 2007; Peterson and Reich, 2008). While Streng et al. (1993) concluded that fire frequency was more important than fire season for sustaining a robust groundflora, they found growing season fires were more effective at killing understory shrubs and hardwoods. Sparks et al. (1998) found the opposite, with late dormant season burns more effective at reducing woody sprouts and improving groundflora abundance and richness. Although managers are looking to use more growing season fire to extend their burn windows, given implementation difficulties (e.g., higher humidities, “greener” fuels, and possible limitations due to wildlife or rare species) and inconsistent results, further study is warranted.

Evidence also strongly suggests that fire can be a much more effective tool if used in concert with other silvicultural treatments (see also Section 4.3). Using only a hot fire to achieve overstory density reduction (sometimes called “thermal” or “pyrogenic” thinning) is possible in some situations (e.g., overstocked stands of variably fire-tolerant tree species), but stands that have not been burned recently can be poor candidates for this treatment due to potentially high mortality of functionally important overstory specimens (e.g., Varner et al., 2005). Although repeated light burns over time may eventually create more open forest structure, the use of prescribed fire only to restore open forests is particularly difficult if a relatively high intensity fire is needed to create partially open conditions; near complete overstory mortality can readily occur when burning at higher intensities in steep terrain (Lorber et al., 2018). Groundflora restoration using only prescribed fire (even after repeated burns) often failed to adequately control sprouting hardwoods and shrubs (e.g., Pittman and Krementz, 2016). Others have found that while prescribed fire alone proved most

cost- and ecologically-effective on xeric longleaf pine sites with intact groundflora (Provencher et al., 2001), burning alone did not yield desired structural or compositional overstory changes in a longleaf pine stand in southern Georgia (Brockway and Lewis, 1997) or simulated upland oak in the Missouri Ozarks (Jin et al., 2018).

### 3.2. The rest of the open forest silvicultural toolbox

While the ecological benefits of fire cannot be entirely replaced by silvicultural alternatives, many other practices offer a number of distinct logistical and implementation advantages in the effective management of open forests. Timber harvesting, whether commercial or non-commercial, can be as vital a tool as prescribed fire in the restoration of open forests ecosystems. Achieving a dramatic reduction in overstory density using commercial timber harvests is the most preferred option, as this may present the best revenue opportunity to support initial and future non-revenue producing restoration efforts (Barrioz et al., 2013; Guldin, 2019). Open forest timber harvests can be tiered to meet more than just stand density targets. Undesired tree species or size classes can be preferentially cut in a more controlled fashion than less selective treatments (e.g., prescribed fire, broadcast herbicides) or when trees targeted for removal are relatively immune, resistant, or tolerant to the alternatives (Dey et al., 2017).

Harvesting can also aid groundflora management. Barrioz et al. (2013) viewed substantial overstory reduction to restore oak savannas as critical due to the positive impacts of harvest on groundflora composition, abundance, and coverage. Deadening timber (called “wildlife stand improvement” by Sparks et al. (1998)), long practiced as a means to rapidly change forest structure (e.g., Galgamuwa et al., 2019) without removing the wood, can involve the girdling of a few live trees to more extensive fell-and-leave operations (Fig. 1). Deadened trees can improve wildlife habitat quality, supplement nutrient cycling and carbon sequestration, and provide needed fuels. However, excessive standing dead timber or logging slash can be problematic if they produce dangerous fire conditions or host undesired diseases, insect pests, or other invasive species. Under this circumstance, follow-up treatments to reduce dead wood (e.g., fire, mastication) can be applied, but will appreciably increase management costs.

Properly applied herbicides can also play an important role in open forest management (although they can be difficult to use on public



Fig. 1. Example of a fell-and-leave deadening in an oak woodland restoration project on the Ozark National Forest in northern Arkansas. Although they attempted to sell this stand commercially, lack of a market led to the felled hardwoods and eastern redcedar being left on the site to decay or be consumed in later prescribed fires. Note the variable density in retained oaks and small stand of shortleaf pine on the top of the ridge—this is done to better emulate historical spatial patterns. Forest Service photograph by Don C. Bragg.

lands). Herbicides can help ensure a desired mix of conifers and hardwoods when other mechanical or pyrogenic treatments may skew strongly towards one or the other (Guldin, 2019). In many instances, selectively active herbicides can be used to target certain categories of undesired vegetation, such as native hardwood trees, woody shrubs, or exotic species (Guo et al., 2018). However, herbicide treatments must be carefully matched to conditions to ensure that unintended consequences are minimized, such as negative impacts on desired groundflora (such as C<sub>4</sub> grasses) affected by the broadcast application of herbicides to control woody shrubs (Platt et al., 2015). Although much less cost efficient, stem injection and basal bark herbicide treatments can reduce midstory and understory tree densities without negative impacts on non-target groundflora (e.g., Kochenderfer et al., 2012). Backpack spraying in bands adjacent to rows of planted longleaf pine was shown to be an effective way to control shrubs without major harm to groundflora (Freeman and Jose, 2009).

Another often overlooked option for the restoration of open forests is the use of artificial regeneration. The mechanical site preparation treatments commonly used to establish commercial tree plantations (e.g., ripping, bedding, mounding) or even general plowing can improve the growth and survival performance of planted seedlings (Löf et al., 2012) as well as naturally regenerated species (e.g., Simpson, 2019). However, mechanical site preparation can aggravate or even introduce invasive exotic species (such as cogongrass (*Imperata cylindrica*)). In former longleaf ecosystems, restoration of open longleaf pine stands often requires the removal of competing pine species, planting longleaf pine seedlings, and increasingly, the planting of preferred groundflora species (Brockway et al., 2016; Hess and Tschinkel, 2017). Once established, these longleaf pine plantations can be managed toward a multi-aged, open forest structure using a regime of thinnings and frequent prescribed fire that establishes young cohorts of natural longleaf pine seedlings (Jack and McIntyre, 2018).

Underplanting trees has also gained acceptance as a tool in ecosystem restoration efforts, as it allows for the supplementation of inadequate natural regeneration, as well as the retention of some of the mature forest structure and related habitat benefits during the conversion process (Kirkman et al., 2007; Arthur et al., 2012; Dey, 2014). Underplanting has been used successfully in some longleaf pine restorations (e.g., Knapp et al., 2013, 2014, 2015b; Hess and Tschinkel, 2017; Jack and McIntyre, 2018). Underplanting in partially cut hardwood forests has been tried in more conventional silvicultural systems to less than ideal outcomes (e.g., Dey et al., 2012), but it may be an option for restoring oak savannas and woodlands (Dey et al., 2017).

Where native groundflora and seed banks have been largely eliminated by long-term fire exclusion, agriculture, or other practices, planting of desired species may be the best—and sometimes only viable—way to restore critical herbaceous components (Brudvig et al., 2013). Mulligan et al. (2002) planted wiregrass in young longleaf pine plantations to good results, even at relatively low planting densities, while wiregrass and 31 “non-matrix” herbs were planted extensively at the Savanna River Site with good survival of most species (Aschenbach et al., 2010). In oak woodland and savanna restorations, direct seeding to enhance groundflora diversity also shows promise (Brudvig et al., 2011) but has rarely if ever been operationally applied. Research suggests that direct seeding can be a cost effective option to restore a depauperate groundflora in longleaf pine forests (Walker and Silletti, 2006; Kirkman and Giencke, 2018).

### 3.3. Silvicultural synergy

As useful as any of these silvicultural tools are individually, their effectiveness often increases when they are combined. So, while returning fire to a forest system after a long absence provides a key ecological process, burning alone may not achieve the desired overstory density reductions or groundflora increases. A meta-analysis showed that fire plus herbicide proved more effective than just burning in

improving biodiversity responses of loblolly pine-dominated forests treated to create an open forest condition (Greene et al., 2016). Invasive species control, often a major concern in open forest restorations, usually benefits from an integrated treatment approach. For cogongrass, an exotic rhizomatous graminoid that forms dense patches and crowds out desired native vegetation, prescribed fire and/or mastication proved to be ineffective control treatments because its rhizomes are shielded from the effects of all but the hottest fires and chopped up rhizomes can spread the species. Better control of cogongrass was achieved with a program of mechanical treatments, prescribed fire, and the use of herbicides such as glyphosate and imazapyr (Dozier et al., 1998). Even native fire-intolerant tree species can be problematic if only fire is utilized for their control. Once established, all hardwood species, including those considered fire-intolerant can resprout when top-killed by fire or harvested, allowing for their continued persistence (Del Tredici 2001). In addition, species like sweetgum (*Liquidambar styraciflua*) can widely disperse from nearby sheltered locations, providing a seed source that can quickly recolonize freshly burned areas. For these persistent woody species, using fire and herbicides together may offer more complete control. As an example, spot application of hexazinone improved the effectiveness of prescribed fire in restoring the groundflora of a longleaf pine-wiregrass community (Brockway and Outcalt, 2000).

Similarly, closed oak and oak-pine systems have shown a much greater positive groundflora response when cutting is coupled with other treatments (e.g., Masters et al., 1996; Kinkead, 2013; Vander Yacht et al., 2017; Bassett et al., 2020). Researchers have found that partial harvesting alone, even when done in canopies dominated by oaks, often failed to result in new oak recruits due to competition with more shade-tolerant (but less fire-tolerant) species such as red (*Acer rubrum*) and sugar (*Acer saccharum*) maples, eastern redbud (*Cercis canadensis*), elms (*Ulmus* spp.), and eastern redcedar (*Juniperus virginiana*) (e.g., Schuler, 2004; Arthur et al., 2012, Galgamuwa et al., 2019). However, multiple cycles of prescribed burns in combination with canopy and midstory removal were shown to shift advanced tree regeneration to fire-tolerant oak and pine (Arthur et al., 2012). Similarly, overstory reductions and midstory/shrub control with mechanical or chemical treatments did little to stimulate the establishment and growth of herbaceous plants in the absence of fire (Sparks et al., 1998; Provencher et al., 2001; Kinkead, 2013; Oakman et al., 2019). Brockway and Outcalt (2015) also suggested that single tree selection and group selection cutting, when coupled with fire, were less risky to established longleaf pine groundflora communities than shelterwood harvests.

## 4. Putting it all together: Case studies and silvicultural considerations for open forests

Although silvicultural systems are gradually adopting multiple (including non-timber) resource priorities and adaptive complexity (sensu Fahey et al., 2018; Franklin et al., 2018), management of most closed forests typically prioritizes high stocking of commercially preferred species, homogenization of structure, shortened rotation lengths, fire exclusion, and other measures to protect and enhance the tree component (e.g., Puettmann et al., 2009; Hanberry and Dey, 2019). While antithetical to open forests, these priorities are logical consequences in closed forest management. As an example, for silviculturists seeking a well-stocked condition, a limited herbaceous groundflora is rarely problematic. After all, well-distributed regeneration of preferred tree species across the available growing space is the desired outcome of any timber production-oriented system, and the biggest challenge is getting those small trees to merchantable size as quickly as possible.

In recognizing the need for alternative priorities, the practice of silviculture in the open forests of eastern North America has been evolving for a number of decades, particularly around iconic species or ecosystems. In this section, we present a set of large-scale case studies

**Table 1**  
A selection of open forest restoration case studies from the eastern US chosen to exemplify different forest types, ownerships, management efforts, and silvicultural options.

Site name and location	Ownership type	Dominant tree species	General site type	Restored area (ha)	Silvicultural system(s) <sup>1</sup> and supporting treatment(s)	Supporting references and materials <sup>2</sup>
Wade Tract, Arcadia Plantation, Georgia	Private	longleaf pine	Red Hills, Lower Coastal Plain	85	UEAS (Stoddard-Neel); prescribed fire	Moser et al. (2002), Masters et al. (2003), Moser (2006)
Jones Center at Ichauway, Newton, Georgia	Private foundation	longleaf pine	Lower Coastal Plain	11740	UEAS (Stoddard-Neel); prescribed fire; underplanting of longleaf pine in some stand conversions	Boring (2001), McIntyre et al. (2008), Jack and McIntyre (2018)
Shortleaf pine-bluestem project, Ouachita National Forest, Arkansas and Oklahoma	Federal	shortleaf pine	Ouachita Mountains	> 62000	EAS (seedtree, coppicing); UEAS (single tree selection); prescribed fire; commercial & precommercial thinning; midstory removal	Hedrick et al. (2007), Stephens et al. (2019)
Warren Prairie Natural Area, Bradley and Drew Counties, Arkansas	State	loblolly & shortleaf pines	Upper West Gulf Coastal Plain	2250	EAS (seedtree, planting of loblolly and shortleaf pines); prescribed fire; commercial & precommercial thinning; some mastication; limited herbicide use	Shepherd et al. (1991), Hollimon et al. (2008), author(s) experiences
Moro Big Pine Natural Area, Calhoun County, Arkansas	Industry	loblolly pine	Upper West Gulf Coastal Plain	6500	EAS (seedtree, planting of loblolly pine); UEAS (in bottomland hardwoods and cypress only); prescribed fire; commercial & precommercial thinning; herbicide to release pine/kill exotics	Bragg et al. (2014), author(s) experiences
Boggy Slough Conservation Area, Houston and Trinity Counties, Texas	Private foundation	shortleaf & loblolly pines	Upper West Gulf Coastal Plain	> 7700	UEAS (single tree selection); EAS (planting of shortleaf pine); prescribed fire; commercial & precommercial thinning; herbicide use to release pine and control exotics	author(s) experiences
Missouri Ozark woodlands, southern Missouri	State	oaks & shortleaf pine	Ozarks	1000s	UEAS (single tree selection); EAS (planting of shortleaf pine); prescribed fire	McCarty (2003), McCarty (2004), Blake and Schnette (2000)
Missouri Pine-Oak Woodlands Restoration Project, Mark Twain National Forest, Missouri	Federal	shortleaf pine & oaks	Ozarks	> 46000	UEAS (single tree selection); EAS (planting of shortleaf pine); prescribed fire; commercial & precommercial thinning	Mark Twain National Forest (2011)
Catoosa Wildlife Management Area, Cumberland County, Tennessee	State	Oaks	Cumberland Plateau	1200	Commercial thinning; prescribed fire; some herbicide use on woody regeneration	Vander Yacht et al. (2017), TWRA (2020)
George Washington and Jefferson National Forests, Virginia	Federal	oaks & pines	Ridge and Valley	> 34000	Only prescribed fire in the restoration areas	Lorber et al. (2018)

<sup>1</sup> UEAS = uneven-aged silviculture; EAS = even-aged silviculture

<sup>2</sup> "Author(s) experiences" indicates locations where one or more of this paper's authors have had personal (but unpublished) experience or knowledge of silvicultural system and/or supporting treatments.

(Table 1) of open forest management as applied in southern pine, “mixedwood”, and oak-dominated forests and discuss some of the logistical challenges when implementing open forest management. All of these case studies apply prescribed fire (although many not as frequently or as effectively as desired (e.g., Lorber et al., 2018)), primarily to support wildlife management goals, and most are continually threatened by overstocking of desired and undesired tree species (both native and exotic), invasive organisms, and a changing climate. The lessons of these case studies, plus experiences of others, can be used to aid practitioners seeking the benefits of open forest ecosystems.

The fact that most of these case studies are in pine-dominated ecosystems illustrates one of the major challenges—we do not know everything we need to know to manage open forests, particularly oak and mixed-composition systems. Even for some of the most studied open forest ecosystems, such as longleaf pine, new questions from managers and challenges arising from local circumstances or the adaptation of general restoration principles on elements such as biological legacies and stand dynamics will continue to confront researchers. Understanding the dynamics of open forests helps to set structural and compositional targets (“expectations” and “endpoints”), acceptable ranges in variation (e.g., Hanberry et al., 2014a; Stanturf et al., 2014b), and may even suggest the best silvicultural system(s) or tool(s) to meet restoration objectives (e.g., Bragg, 2004). For instance, research on downed dead wood in old-growth longleaf pine has noted



a.



b.



c.



d.

Fig. 2. (continued)

Fig. 2. Examples of open pine-dominated forests from the southern US. Longleaf pine from the Red Hills of southern Georgia: (a) old-growth on the Arcadia Plantation; (b) second-growth forests of the Jones Center at Ichauway, both with characteristic open conditions and longleaf regeneration in canopy gaps of both locations; (c) a recently—and repeatedly—thinned and burned even-aged, loblolly pine-dominated open stand in the Moro Big Pine Natural Area in southern Arkansas; (d) a mature, naturally regenerated, restored shortleaf and loblolly pine forest on Boggy Slough Conservation Area in eastern Texas. Forest Service photographs by Don C. Bragg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

its relative rarity, likely due to a combination of losses via frequent fire, rapid decay rates, and consumption by detritivores (Ulyshen et al., 2018). Hence, restoration of open longleaf pine forests by thinning the mid- and overstories followed by logging slash reduction may quickly produce overstory and dead wood quantities consistent with known reference conditions.

Unfortunately, many of the open southern pine forests on the most productive sites were converted many decades ago to either agricultural lands or closed canopy forests (now often industrially managed loblolly or slash pine (*Pinus elliottii*) plantations) (Fox et al., 2007; Bragg, 2008; Carter et al., 2015; Anderson et al., 2016; McIntyre et al., 2018), leaving very few remnants to serve as models of open forests (Bragg, 2002; Bragg, 2008). Another primary contributor to the loss of open southern pine reference ecosystems was the widespread reduction or elimination of surface fires that maintained the open structure (Frost, 2006; Hanberry et al., 2018). The net result of these conversions and transitions was the widespread and still-continuing loss of functional longleaf and shortleaf pine examples from which to develop reference conditions. When coupled with a changing climate, increasing numbers of invasive species, and landscape- and regional-scale fragmentation, researchers and managers will have to look for new opportunities to understand and restore open forest ecosystems.

Second, even with silvicultural methods that seek to mimic the natural disturbance regime, it will be a challenge to get most managed forests to emulate historical open forest conditions. Some of the best contemporary examples of functional open forests are the hunting properties in southern Georgia and northern Florida (Table 1; Fig. 2a and b). Their well-tended old-growth and managed second-growth longleaf pine, maintained using frequent prescribed fire and the application of uneven-aged silviculture (Boring, 2001; Moser et al., 2002; Jack et al., 2006; McIntyre et al., 2008; Mitchell et al., 2009a; Way,

2011; Jack and McIntyre, 2018), have long balanced their timber, wildlife, ecological and diversity objectives. For decades, these “shooting plantations” have benefited from the Stoddard-Neel system, an inherently conservative uneven-aged silviculture approach that maintains a multi-aged forest structure with varying but typically low (< 15 m<sup>2</sup>/ha) basal area using prescribed fire and periodic harvests of high-value large longleaf pines to generate modest revenues (Moser et al., 2002; McIntyre et al., 2010). Low densities of mature longleaf pine produce sufficient needles and other fuels to support frequent prescribed fires (and the resulting diverse groundflora), occasional commercial timber harvests, and perhaps most critically, lucrative hunting operations (Landers et al., 1989; Masters et al., 2003; Moser, 2006). These hunting plantations are more an exception than the rule; such economic benefits are much less available for most open forest silvicultural implementations.

The fact that internal structural or compositional overstory variation is lower in open forest ecosystems helps to simplify some aspects of their management. In the Ouachita Mountains of Arkansas and Oklahoma, the mature, mixed forests of the Ouachita National Forest (Table 1) were relatively easily modified from closed canopy shortleaf pine-hardwood stands to open shortleaf pine-bluestem woodlands using a combination of frequent prescribed fire, overstory harvests, and midstory hardwood removals. This allowed for rapid and large-scale (over 62000 ha) restoration of open forests using a combination of seed tree and single-tree selection to increase RCW populations and meet other ecosystem management goals (Hedrick et al., 2007; Stephens et al., 2019). Again, the commercial viability of this particular effort (with salable volumes of pines and hardwoods) supported its implementation at scale—especially since the existing overstory contained more than enough shortleaf pine.

Commercial viability has also been the case for a number of open forest restoration projects in the productive uplands of the Upper Coastal Plain. For example, the Moro Big Pine Natural Area (Table 1; Fig. 2c) is a nearly 6500 ha corporately-owned property on a pine flatwood-dominated landscape in southern Arkansas with a significant timber production requirement in addition to a conservation easement to improve RCW habitat and encourage other open forest-associated species (Bragg et al., 2014). Unlike many other open pine woodland restoration efforts, Moro Big Pine uses relatively short rotation lengths (approximately 50 years) in its even-aged natural-origin loblolly pine stands, with regular herbicide applications to control unwanted species and frequent thinnings to boost pine growth. Similar experiences have been found in the loblolly and shortleaf pine-dominated stands of the state-owned Warren Prairie Natural Area in southeastern Arkansas and the privately owned Boggy Slough Conservation Area in eastern Texas (Table 1: Fig. 2d), which also have long histories of commercial timber harvests and prescribed fire to support hunting and other recreational activities.

While they use different approaches, the longleaf pine hunting plantations, Moro Big Pine, Boggy Slough, and Warren Prairie all share sustaining RCW habitat as a management priority. The fact that the mature, open, southern pine-dominated forests required by this woodpecker permits an overstory simplicity also allows for certain silvicultural situations to be transitioned from an intensive management to open forest condition. Hence, even monoculture plantations of southern pines can be converted into functional open forests under the proper application of system restoration treatments (e.g., prescribed fire), judicious thinnings, and greatly extended harvest rotations (Guldin, 2019). Indeed, some of these converted plantations (Fig. 3) can be hard to distinguish from comparable stands of natural origin. Regrettably, this is often not the case in many mixedwood or oak-dominated open forests, for which regeneration is more challenging, good timber markets do not exist, and rotation ages are much longer.

Third, it is important to recognize that practices in the open forests of eastern North America require different emphases than silviculture of closed canopy forests. For example, silviculture to restore oak-



Fig. 3. An example of planted longleaf pine on the Vernon District of the Kisatchie National Forest in central Louisiana being gradually converted to open forest conditions using periodic overstory thinnings and frequent (once every 2–3 year) prescribed fire. These 70+ year old pines were originally planted to restore commercial forest cover to landscapes so heavily cutover that no seed trees had remained; over the decades, management objectives focused more on improving habitat conditions for species such as the RCW than timber production. Forest Service photograph by Don C. Bragg.

dominated woodlands and savannas generally includes two phases: restoration and maintenance (e.g., Dey et al., 2017, Johnson et al., 2019). During the restoration phase, prescribed burning (with or without thinning) is used to reduce tree density in the midstory and thin the overstory to enhance the development of the ground vegetation. Open forests are inherently “understocked” using the metrics of production forestry—at maturity there will only be about 75 to 100 canopy dominant or codominant trees per hectare in oak woodlands and 40 to 50 trees per hectare in savannas (e.g., Dey et al., 2017). The duration of the restoration phase is five to twenty years but generally lasts until the desirable structure and composition has been achieved. A recent, large scale (> 46000 ha) effort (Table 1) on the Mark Twain National Forest looking to restore open oak-, oak-pine-, and shortleaf pine-dominated forests using prescribed fire, commercial timber harvests, and midstory removals has just entered this restoration phase (Mark Twain National Forest, 2011), as have several other Collaborative Forest Landscape Restoration Program projects in the eastern US.

To create sufficiently open forest conditions, first-entries in dense stands may remove from 60% to 90% of all stems. Rather than focusing on vigorous crop trees, those retained include large, dominant oaks with spreading crowns. An overall stocking of 55% to 75% is targeted for restoring closed-canopy oak woodlands, while stocking levels of 30% to 55% are desired for open-canopy oak woodlands and stocking levels < 30% are sought to restore savannas (Hanberry et al., 2014a; Vander Yacht et al., 2017). Further, reducing stocking to such low levels is usually done with little regard for the accumulation of advanced tree regeneration (Steventon et al., 1998; Anderson and Crompton, 2002; Harrison et al., 2005; Schieck and Song, 2006; Rosenvald and Löhmus, 2007). This reduction may seem drastic, particularly when compared to traditional approaches that retain enough residual stocking to ensure good tree regeneration and high levels of wood production. However, unlike comparable thinning practices in commercially managed, closed-canopy stands, these harvests are not intended to encourage tree regeneration, nor are they focused on increasing the growth of residual trees or favoring preferred timber species (all of which may happen). Rather, these density reductions are designed to free resources (light, water, nutrients) for the herbaceous groundflora characteristic of open forests.

To sustain the arboreal component of open forests, regeneration is not continuously required. Establishment of new trees is made more difficult by the groundflora’s high cover and biomass, resulting in

relatively stable understory communities over time under a regime of frequent fire (Palmquist et al., 2015). When trees need to be regenerated and recruited under a frequent, low-intensity fire regime, uneven-aged silviculture methods including single-tree and group selection can be applied. Where longer fire-free periods are required for successful regeneration and recruitment, even-aged silviculture methods are more appropriate because they allow for the exclusion of fire until a desired number of trees are large enough to avoid being top-killed when the fire regime is resumed. Suitable even-aged silviculture regeneration methods are those that allow for the permanent retention of large or desirable trees such as with the seed tree method with reserves or irregular shelterwoods. Decisions for which overstory trees to retain in open forests also can differ from traditional forest management practices since the quantity of propagules is no longer paramount, but rather the need to balance important structural attributes (e.g., retention of cavity trees), vigor (likelihood of residual tree survival, both short- and long-term), log quality, and fecundity.

Sometimes, a more gradual reestablishment of desired species through natural regeneration or underplanting is sought. For example, research has shown that attempts to restore native longleaf pine on lands converted years ago to slash pine plantations using large group openings (patch clearcuts) and prescribed fire were unsuccessful due to a lack of fuel continuity to carry fires through the large canopy openings (Hess and Tshinkel, 2017). Similar problems with carrying fire through an understory dominated by woody vegetation (rather than finer fuels) have also been noted in restoration efforts that plant longleaf pine after clearcutting a loblolly pine overstory, favoring partial overstory retention to limit woody regrowth (Knapp et al., 2014). In both of these examples, the loss of pine needle litter from overstory slash or loblolly pines, coupled with less flammable woody regrowth, significantly hindered the effectiveness of prescribed fire in controlling groundflora condition and structure.

Fourth, open forest restoration is almost universally an iterative and phased process, with multiple restoration entries and treatments usually required before the stand moves into a maintenance phase. For example, experience has shown that simply opening the canopy coupled with one treatment of low intensity burning was insufficient to favor fire-resistant advanced regeneration (Hanberry et al., 2017). Other large-scale efforts to create open forest conditions using prescribed fire only, such as on the George Washington and Jefferson National Forests in Virginia (Table 1), have found single or even several prescribed fires have failed to meet their ambitious restoration targets although some progress was made (Lorber et al., 2018). The Fire and Fire Surrogate Study in the southern Appalachians reported that mechanical thinning followed by repeated burns (4–5 year return intervals) over nearly two decades resulted in an understory dominated by shrubs and tree seeding/sapling sprouts rather than a robust herbaceous groundflora (Waldrop et al., 2016; Oakman et al., 2019). However, intermediate stages of structural restoration should be viewed as incremental improvements, as opened forests with a shrubby groundflora layer can still provide useful wildlife habitat (McCord et al., 2014; Greenburg et al., 2018).

Once acceptably restored, mixedwood and oak woodland and savanna management shifts to a maintenance phase. Retaining a residual overstory at the 10% to 30% stocking range (for a savanna) or 30% to 75% stocking range (woodland) to provide habitat and retain “character” trees provides partial shade which can help reduce the woody regrowth surrounding the residual trees and allow some of the ground flora to be partially retained (Hanberry et al., 2014a, 2017b; Dey et al., 2017). If relatively high levels of overstory stocking are acceptable, then prescribed fire alone may be able to maintain the desired density, and these prescribed burns can happen less frequently—perhaps once every five to as much as thirty years—to retain the open structure and desired herbaceous groundflora. Thinning may be used in the maintenance phase only where specific trees have been identified for removal to maintain stocking goals. The stocking level can be reduced

through commercial harvesting if there is sufficient merchantable material; otherwise, non-commercial thinning from below can be done to meet desired stocking levels. A number of Missouri agencies have reached this maintenance stage in some state parks in this region in the Ozarks (Table 1), after prescribed fire and limited commercial harvests reduced the midstory and removed fire-intolerant taxa while restoring desired groundflora (McCarty, 1993; McCarty, 2004; Blake and Schuette, 2000).

At some point during the maintenance phase of open forests, it becomes necessary to replace a significant number of trees that have been lost to mortality due to old age, stress, or pest and disease problems. When and where this becomes necessary, a new cohort of trees will need to be recruited into the overstory. In some open oak forests, overall stocking needed to be reduced to 10% to 30% to allow for the accumulation of seedling and sprouted oak advance reproduction during the maintenance phase (Kabrick et al., 2014; Dey et al., 2017). Many oak species, for example, resprout vigorously when top-killed as young trees, and these sprouts are often more abundant and competitive than acorns for the reestablishment of oak-dominated overstories (e.g., Dey et al., 2008; Dey, 2014). However, older hardwoods (including oaks) are less capable of sprouting, adding to the difficulty of regenerating mature stands (Dey, 2014). Similar accumulation of advance southern pine recruits (especially in shortleaf and longleaf pine) can also be done (see Fig. 2 for examples). Once sufficient numbers of advance reproduction have been achieved, prescribed fire should be excluded long enough to allow the new cohort to escape being top-killed by fire (Arthur et al., 2012; Johnson et al., 2019).

Fifth, managers looking to restore open forest conditions must be willing to think creatively when it comes to silvicultural treatments. While fire is a universal consideration for the restoration of open forests in the eastern U.S., and more conventional applications of harvests and herbicides have steadily grown in favor, other treatments may need to be considered. For example, mastication (the grinding of wood into small pieces) is being increasingly applied where large volumes of fuel need to be reduced quickly and at lower risk than treatments such as herbicide application followed by prescribed fire. The masticated trees can serve as a mulch, which may help some understory species by reducing competition and hinder others by inhibiting establishment or growth. In the short-term, mastication can increase groundflora cover and diversity, but frequent fire will still be needed to limit the re-development of dense shrub and midstory layers (Brockway et al., 2009; Black et al., 2019). However, mastication has its own challenges, from being expensive and potentially detrimental to important habitat components such as large downed wood to aiding in the expansion of invasive species (Black et al., 2019).

Conventional forestry wisdom often discourages what may be viable vegetation management options for open forests. For example, herbivory once helped sustain the grass-dominated groundflora of open forests, first by native ungulates and then later by livestock (e.g., Ray and Lawson, 1955; Considine et al., 2013; Veldman et al., 2015; Hanberry et al., 2020). However, foresters have long eschewed the practice of grazing (browsing) forests because of its potential to damage to crop trees, suppress desired tree regeneration (or favor undesired trees), and spread of invasive species (e.g., Tillotson and Greeley, 1927). While overabundant herbivores (including native species such as white-tailed deer (*Odocoileus virginianus*) and eastern cottontail rabbit (*Sylvilagus floridanus*)) can overconsume desirable groundflora and needed tree regeneration (e.g., Popay and Field, 1996; Dey et al., 2008; Harrington and Kathol, 2009; DiTommaso et al., 2014; Pruszenski and Hernández, 2020), when properly used, reintroduced native ungulates (e.g., *Bison bison*) and domesticated livestock can help restore and maintain open forests (e.g., Harrington and Kathol, 2009; Considine et al., 2013; Dey et al., 2017). Herbivory can provide vegetation control in areas where controlled surface fires, herbicides, or mechanical removals are untenable due to air quality restrictions, local use regulations, cost, or fire escape liability issues (e.g., Webb, 1977; Ray and

Lawson, 1955; Lovreglio et al., 2014; Hanberry and Abrams, 2019). Goats (*Capra aegagrus hircus*) in particular are an option as they are capable of consuming understory woody vegetation and invasives often shunned by other grazers (Luginbuhl et al., 2000; Lovreglio et al., 2014). Modest levels of livestock grazing can help some landowners keep their open forest ranges because it provides both supplemental income and a means to control undesirable woody vegetation (e.g., Adams, 1975; Garrett et al., 2004).

Finally, the specific silvicultural system applied in an open forest may be chosen not because it is the most efficient way to harvest timber or ensure future wood production, but rather because it is more likely to produce desired conditions. For this reason, many managers prefer some type of variable retention harvest practices designed with specific structural and compositional goals to produce a better approximation of open forest ecosystems. Research has suggested that historical open forests experienced overstory mortality as a largely individualistic process, with few disturbances sufficiently intense or extensive to cause widespread canopy tree loss. In the denser portions of the open forest spectrum (e.g., woodlands), gap dynamics could occur, sometimes in even-aged patches. As a result, and when combined with localized differences in site nutrients and moisture, complex spatial (horizontal) patterns arose and it was common for open forests to have an uneven-aged structure (Hanberry et al., 2018). These complex patterns also create greater heterogeneity in understory environments, capable of supporting greater site-level groundflora diversity (Leach and Givnish, 1999).

## 5. Financial viability of open forest silviculture

One of the biggest obstacles to overcome when managing for open forests is its impact—real or perceived—on traditional timber outputs and long-term financial viability of these systems. Obviously, the presence of functioning timber markets coupled with commercial amounts of pine and hardwood can greatly facilitate restoration treatments. Even still, open forest management will rarely prove as lucrative as more conventional commercial systems. This is particularly true in inaccessible, hard-to-log, hardwood-dominated landscapes (e.g., rugged hills) or places where butt log quality has suffered from repeated prescribed fires (e.g., Dey and Schweitzer, 2018; Mann et al., 2020). Furthermore, dense stands of small diameter timber can be very difficult to harvest commercially and generate revenue, especially when local markets for pulpwood, fuelwood, chips, or pellets are lacking. Even when large-diameter timber is available for sale in restored areas for higher-value products (e.g., sawtimber, veneer, cabin logs, poles), the sometimes limited quantities of wood available, the unsuitability of the harvested species for high value products, or social resistance to commercial logging can prevent timber cutting from being economical. These difficulties are why public agencies often support restoration treatments with stewardship contracts (Moseley, 2010).

While these challenges are most noticeable in many oak woodlands, they can also occur with higher productivity pine sites. The shortleaf pine-bluestem restoration efforts on the Ouachita National Forest have been projected, for example, to result in long-term declines of about 25% in timber revenues over the lifespan of the effort due to lesser removals over time and greater management expenditures for elements such as RCW habitat (Zhang et al., 2010; 2012). With few exceptions (e.g., McIntyre et al., 2010), little long-term and large-scale economic analysis has been done in managed open forest ecosystems, making them very difficult to place in context. While some locations have a way to value non-timber considerations (e.g., improved quality of game hunting, such as northern bobwhite quail (*Colinus virginianus*) in open longleaf pine forests), how does one tally the benefits of other less marketable ecosystems goods and services? For example, oak savanna restoration has been shown to greatly increase the abundance and diversity of bees and other pollinators (Grundel et al., 2010; Lettow et al., 2018) by increasing nectar sources and providing supporting habitats.

Similarly, creating or restoring open forest conditions for the RCW has provided large areas of habitat suitable for many other noncommercial species (Conner et al., 2001; James et al., 2001). Unfortunately, these non-commodity values have proven difficult to capture in financial analyses (Caputo, 2012).

Though changing the focus from timber production (with its clear monetary return) to one based on less tangible goods and services (e.g., the value of pollinators or insect pest predators such as bats) will lessen cash receipts, a different way to view the returns of open forest silvicultural treatments is not how they may maximize income, but rather how they can offset the costs of restoration and habitat improvement. On public lands, this has greatly increased the scale of possible restorations and how often they are attempted, especially given the limited funds typically available for habitat improvement or species protection (Hedrick et al., 2007; Stephens et al., 2019). Commercial timber harvests, even if not focused on maximizing revenue, can help keep structurally restored open forests self-supporting and therefore more sustainable, as has been the experience with the shortleaf pine-bluestem restoration of the Ouachita National Forest (Stephens et al., 2019) and some open pine work in Georgia (e.g., Moser et al., 2002; McIntyre et al., 2010). Under some circumstances, other revenues can offset diminished returns from timber. For example, the private owners of the Moro Big Pine project in southern Arkansas (Table 1) agreed to a conservation easement that required they forgo using more fiber productive short-rotation loblolly pine plantations and instead combine even-aged natural regeneration (seedtree harvests) practices with payments from carbon credits (Bragg et al., 2014).

## 6. Conclusions

Intensive forest management can come at high conservation costs, and hence silviculture has been increasingly scrutinized for its emphasis on commodities such as dimensional lumber, pulpwood, or veneer (e.g., O'Hara et al., 1994; Kerr, 1999; Puettmann et al., 2009, 2015; Ciancio and Nocentini, 2011; Caputo, 2012; O'Hara, 2016). The demand for alternatives has increased as public land managers, non-governmental organizations, and even private owners, responding to criticism and compelled by policies, regulations, directives, sustainability initiatives, and other motivations, have pursued a different suite of treatment opportunities and management priorities (Caputo, 2012). Under an approach to ecosystem restoration that deemphasizes both commodity production and hands-off preservation of open forests, silvicultural treatments oriented towards a functional renewal of degraded ecosystems for the benefit of all goods and services are now being pursued, rather than simply reforestation or afforestation (revegetation) to support timber production (Stanturf et al., 2014a). This transition allows silviculturists to restore, manage, and maintain open forest ecosystems using most of the same tools, technologies, and practices as more traditional approaches—as well as new options—while directing their efforts towards improving the structure, maintenance, and persistence of a groundflora dominated by native fire-adapted grasses, forbs, and sufficient numbers of fire-tolerant tree seedlings.

Another of the most apparent lessons from this synthesis is that managing for open forest conditions is far more effective (in terms of outcome, pace, and scale) when active silvicultural interventions are applied—and usually when used in concert with each other. With the notable exception of restoration treatments being applied to largely intact and functional open forest ecosystems (e.g., burning in quail hunting plantations; Masters et al., 2003), the application of a radical thinning to reduce overstory basal area to savanna or woodland thresholds or the reinitiation of prescribed fire alone are not likely to achieve sustainable results, even if some initial positive responses arise. Further, simply setting aside a property, even if currently in a maintenance state, to protect open conditions (i.e., passive management with no treatment activities) will only succeed in a few very rare circumstances where extreme site or climate conditions occur that would

inhibit the eventual domination of woody plants and the formation of a dense midstory and closed forest canopy. For more productive sites, silviculture must replace the processes that once ensured the desired structure, composition, and function.

In highlighting and synthesizing what we know about open forest management, we recognize that more research is still needed on the efficacy of various treatments to achieve desired results. This is particularly true for oak and mixedwood-dominated ecosystems, which have not been studied as thoroughly as southern pines. Furthermore, a continuously changing environment will almost certainly mean that treatments which worked well for a given site in the past may prove to be less effective or even a spectacular failure in the future. After all, not only is the regional climate changing, but landscapes continue to fragment, new invasive species are being introduced (and existing ones continue to spread), human populations continue to expand (with their added demands for ecosystem goods and services), and new management options rise as others wane (e.g., Wear and Greis, 2013; Shifley and Moser, 2016). Making the inevitable financial trade-offs in open forest silviculture to support less tangible—but equally important—management objectives will continue to limit its widespread adoption. Despite these challenges, our increased understanding of the structure and function of open forest systems should help provide guidance for the restoration and management of its many conservation values.

#### 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.

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#### Disclaimers

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