ECOLOGICAL SILVICULTURAL SYSTEMS

Exemplary Models for Sustainable Forest Management

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Ecological Silviculture for Southeastern US Pine-Oak Forests

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6.1 Introduction

In the southeastern United States, pine (*Pinus*) and oak (*Quercus*) species may co-occur across a wide range of site types and exist in a diversity of assemblages. The geographic focus of this chapter is the vernacular region of the United States Upland South (Figure 6.1). In this region, oak species diversity is high, and these species occur in almost every forest type. Although oaks can share dominance with all pine species native to this region, our focus is on mixtures of oak species that most frequently occur in association with shortleaf pine (*Pinus echinata* Mill), loblolly pine (*Pinus taeda* L.), and Virginia pine (*Pinus virginiana* Mill.), where under management these taxa may co-occur in the overstory. The oaks most frequently found in association with these pines include northern red oak (*Quercus rubra* L.), southern red oak (*Quercus falcata* Michx.), scarlet oak (*Quercus coccinea* Muenchh.), black oak (*Quercus velutina* Lam.), white oak (*Quercus alba* L.), chestnut oak (*Quercus montana* Willd.), and post oak (*Quercus stellata* Wangenh.).

Stands that contain mixtures of pines and oaks in this region can be classed as pine-oak or oak-pine dominant and the species of each genus may vary in their basal area contribution. Recently, the term mixedwoods has been applied to these assemblages. Mixedwood forests are those that contain a mixture of hardwood and softwood species, with neither exceeding 75–80% of stocking based on basal area or canopy cover [1]. The stand types discussed in this chapter fit this definition of mixedwoods. We make no distinctions between pine-oak and oak-pine ecosystems. In such stands, species from other genera may share canopy dominance with these taxa, including hickories (*Carya* spp.), tulip-poplar (*Liriodendron tulipifera* L.), sweetgum (*Liquidambar styraciflua* L.), and red maple (*Acer rubrum* L.) among others.

6.2 Characteristics of Pine-Oak Ecosystems

Pine-oak ecosystems are variable in species richness, canopy cover, tree density, basal area, and other factors. This variability is attributed in part to the diversity of site conditions that support pine-oak mixtures, land use, and management history and the range of species from these genera

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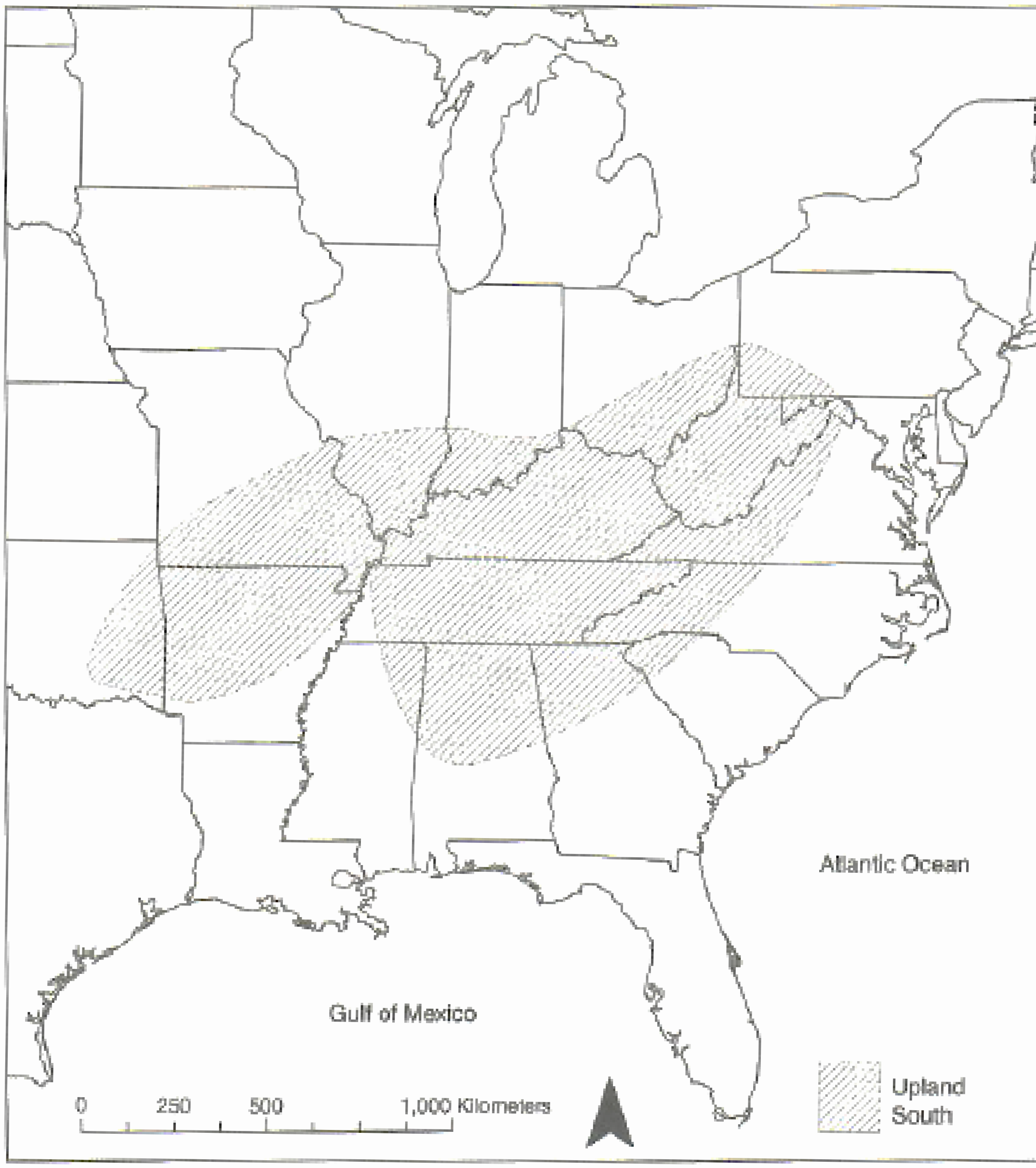

Figure 6.1 The vernacular region known as the Upland South of the eastern United States defined by landforms, history, and culture.

that may be dominant. Pine-oak mixtures can occur as savannas, woodlands, or forests depending on the management goals and disturbance regime (Figure 6.2). As previously stated, species diversity in this region is high and the differences in shade tolerance, growth rate, and life span among the oaks and pines are important drivers of species regeneration and competition dynamics (Table 6.1).

6.2.1 Silvics of Common Species

In general, the pines are more shade-intolerant, faster-growing, and disturbance-dependent species, relative to the co-occurring oaks. Loblolly pine, shortleaf pine, and Virginia pine all require bare or nearly bare mineral soil for seed germination and seedling establishment. Germination is

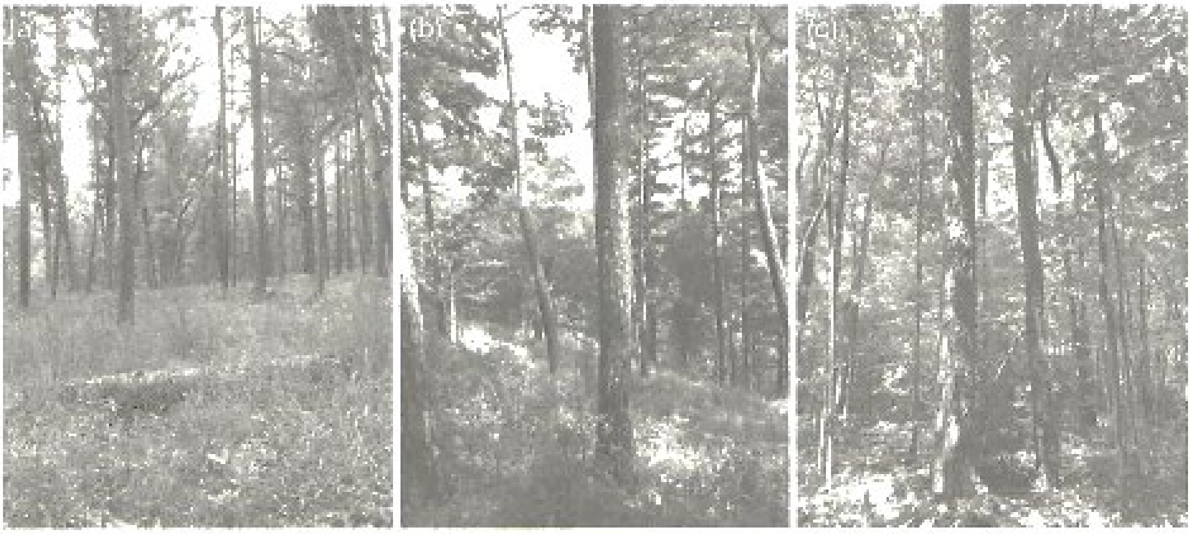

Figure 6.2 Pine-oak mixedwoods in the southeastern United States may occur as savannas (a), woodlands (b), or forests (c) depending on the management and disturbance regime.

Table 6.1 Shade tolerance, moisture affinity class, and approximate maximum lifespan for selected pine and oak species that commonly co-occur in pine-oak mixedwoods of the southeastern United States.

Species	Shade tolerance	Moisture affinity class	Maximum life span (years)
Black oak	Intermediate	Subxeric	250
Chestnut oak	Intermediate+	Subxeric	425
Loblolly pine	Intolerant	Submesic	250
Northern red oak	Intermediate	Submesic	325
Post oak	Intolerant	Xeric	400
Scarlet oak	Intermediate	Xeric	215
Shortleaf pine	Intolerant	Subxeric	325
Southern red oak	Intermediate–	Subxeric	145
Virginia pine	Intolerant	Xeric	130
White oak	Intermediate+	Submesic	470

Intermediate + indicates closer to the tolerant class and Intermediate – indicates closer to the intolerant class.

epigeal and occurs in the spring. Shortleaf pine, which is increasingly prioritized within pine-oak ecosystems by managers, is well-adapted to frequent fire because it can resprout from a basal crook that contains dormant buds. The unique ability of shortleaf pine to resprout after shoot mortality is competitively advantageous compared to other pine species in frequent-fire systems. Pines are noted for their rapid bark growth from early ages which confers protection of the cambium from fire, an advantage they gain earlier in life than hardwoods. Growth rates of pine species are inversely related to shade. Generally, pines growing in the open can outgrow oaks given equal initial tree sizes, but well-developed oak advance reproduction as large seedling sprouts can rapidly suppress young pine regeneration [2]. Loblolly pine tends to dominate on more mesic sites and Virginia pine on more xeric sites. The pine species discussed here are considered drought tolerant and their drought tolerance may be enhanced by management practices, such as thinning. Virginia pines have been documented to live for over 100 years, loblolly pines for over 200 years, and shortleaf pines for over 300 years.

In mixed pine-oak stands, oak species are more shade tolerant than co-occurring pines. Chestnut oak and white oak are generally more shade tolerant than other oak species considered in this chapter. Southern and northern red oak and black oak are intermediate in shade tolerance, and scarlet oak and post oak are shade intolerant. Sources of oak reproduction include seed, seedling sprouts, and stump sprouts. In general, oaks have slow shoot growth as new seedlings as they preferentially allocate growth to roots. Consequently, they have low regeneration potential compared to their competitors in open environments.

Since most oaks decrease in their ability to produce stump sprouts as they grow larger in diameter and age, the main competitive source of oak regeneration is large advance reproduction, i.e. seedling sprouts that accumulate over multiple acorn crops and grow with sufficient light in the understory [3]. Many oak species can develop as large advance reproduction under 30–50% full sunlight in forest understories, and the survival and growth of the more intolerant species improve with increasing levels of light.

Oaks have fire-adapted traits that permit them to persist in frequent fire regimes such as root-centric carbon allocation and dormant, adventitious buds clustered around the root collar that is often buried in soil [4, 5]. Older, larger-diameter oaks have relatively thick bark that protects their cambium from fire. Many oak species are resistant to drought and have flammable litter characteristics that promote fire during dry periods. Species in the red oak group normally live about 80–150 years. Those in the white oak group are much longer lived with life spans that can extend to over 400 years. Oak species from xeric environments such as post oak, white oak, and chestnut oak are more drought resistant and persistent in the face of recurring droughts than are red oak species [6], and white oak species are in general more adapted to droughts than red oaks.

6.2.2 Disturbance Ecology

Pine-oak stands are considered mid-successional, and these mixtures cannot typically be maintained without a combination of canopy disturbance and surface fire. Wind-related canopy disturbance is common in mixed pine-oak ecosystems. Oak decline, caused by complex interactions of environmental stresses and pests, can result in substantial mortality of mature oaks, especially those in the red oak group. Ice storms occur in mixed pine-oak ecosystems and in some locations occur at relatively short intervals (30–40 years). Native insects produce canopy disturbances by causing mortality in mature pines with southern pine beetle (*Dendroctonus frontalis* Zimmermann) being the most common and widespread. Fire may result in canopy tree mortality, but is primarily a disturbance of the subcanopy strata.

Canopy disturbances in mixed pine-oak ecosystems range from highly localized events that remove trees individually to catastrophic events that remove most overstory vegetation. Intermediate-severity disturbances are those that are larger in extent than canopy gaps, but are not stand replacing. The return interval of these disturbances in this region ranges from 20 to 50 years [7, 8]. Disturbance impacts on species composition, stand structure, and ecosystem function vary by disturbance agent, spatial extent, frequency, and intensity. Some disturbance agents are species or genus-specific and those that are not, may disproportionately damage or kill some taxa over others.

Fire is an important disturbance agent in mixed pine-oak ecosystems. Low-intensity fire reduces leaf litter, exposes bare mineral soil, and prevents the development of a duff layer. Fire also causes shoot mortality of small diameter (<10 cm diameter) woody stems. Resprouting is an important aspect of regeneration and competition in pine-oak ecosystems. Although they can resprout, frequent fire inhibits recruitment into larger size classes. Thus, a sufficiently long fire-free period may be needed to recruit oak-pine into the overstory [9]. Fire behavior is in part a function of fuel composition, structure, loading, and flammability, and these characteristics may be highly variable in pine-oak stands. Flammability of litter varies by species and overstory composition. The pines discussed here have highly flammable litter, and so too do oaks common in xeric environments such as white oak, turkey oak, southern red oak, and post oak [10]. Frequent fires can increase herbaceous diversity and cover especially when combined with overstory mortality. Historical fire frequency in this region averaged 4–15 years before European colonization, with spatial and temporal variation in fire severity, season, size, and frequency [11]. Almost universally, fire frequency increased throughout the eastern United States with European settlement with mean fire intervals ranging from one to five years until the fire suppression period of the early 1900s [12].

6.3 Development Model

Development of pine-oak stands is strongly influenced by the pre-disturbance stand condition. Especially important in the pre-disturbance stand is the presence or absence of oak advance reproduction. We note that many contemporary pine-oak ecosystems did not develop following natural disturbance and instead established on abandoned agricultural lands or in abandoned pine plantations. The natural development model presented here begins with canopy disturbance and legacy creation and proceeds through young, mature, and old forest stages. We note that regenerating disturbances in pine-oak stands are more typically intermediate-severity events (i.e. intra-stand scale) and are not stand replacing. Thus, a single pine-oak stand may contain neighborhoods in different developmental stages.

6.3.1 Disturbance and Legacy Creation

Development after canopy disturbance in pine-oak stands is strongly influenced by ecological memory as hardwood rootstocks typically persist in the understory as advance reproduction. Thus, the presence of hardwood rootstocks or other advance reproduction will strongly influence stand development. In pine-oak ecosystems, natural stand-scale catastrophic disturbances are not common. However, natural intermediate-severity disturbances typically occur within stands once every 20–50 years. These disturbances result in legacies of deadwood structures and surviving trees. Sizes, shapes, and configurations of natural disturbance-created openings vary widely depending upon the disturbance agent and disturbance severity. For example, wind disturbances typically remove the largest stems and in pine-oak systems, those are often pine species. These disturbances often create patches of dead trees and residual trees within disturbed neighborhoods may be aggregated or dispersed.

6.3.2 Preforest Stage

The preforest stage in pine-oak ecosystems is relatively short with no true herb-dominated period, given the ability of many species to sprout or establish advance reproduction. The duration of this period may be influenced by the fire regime. Open canopy conditions in these systems often support high species richness and cover of ground flora.

6.3.3 Young Forest Stage

Although pine species typically grow faster than co-occurring hardwoods in open environments, sprouting from well-developed hardwood advance reproduction may negate the height growth advantage of pines that regenerate from seed. When grown from seed, young oaks that typically allocate resources preferentially to root growth can be overtopped by taxa with rapid rates of shoot growth. However, oak shoots originating from well-developed root systems grow faster than those originating from seed when released by disturbance. In addition, mature pine-oak stands may have advance oak reproduction in the understory owing to the greater shade tolerance of oaks. Shortleaf pine, with its ability to resprout, may develop into large advance reproduction under certain low-density stand conditions, however, its reproduction cannot survive in the low light environment of fully-stocked stands.

The density and size of oak stems in the regeneration layer may be promoted by fire in these systems if understory light levels exceed 20% of full sunlight, levels too low for pine reproduction development. If oak advance reproduction is present at the time of canopy disturbance, those stems have a height growth advantage over pine stems that will originate from seed. In these scenarios, naturally regenerated pine should still occur on the site, but will typically be less abundant than oaks. Site conditions are important as pine regeneration is usually more competitive on lower-quality sites. The pine component may exhibit spatial clumping coincident with neighborhood-scale environmental conditions. Regardless, fire and canopy disturbance are required to maintain pine regeneration and recruitment in what may otherwise develop into an oak-dominated system.

6.3.4 Mature Forest Stage

As stands mature, oaks and other hardwoods establish in the pine understory as pines in the canopy senesce. Once the oaks and associated hardwoods establish, the two-aged stands develop as stratified mixtures at taxon-specific growth rates. In this scenario, fire may inhibit the recruitment of the more shade-tolerant oaks and associated hardwoods and relegate them to seedling and sapling size classes. Fire alone will not maintain pine dominance in these systems except on the most xeric sites, but fire frequency is important for pine recruitment into the overstory. Canopy disturbance events are also important to allow sufficient light to reach the regeneration layer. Thus, the combination of fire and canopy disturbance is crucial for maintenance of pine-oak stands. Clearly, intra-stand spatial patterns are important, as fire behavior will vary through a stand with canopy disturbance events occurring stochastically. For example, even in a stand subjected to frequent prescribed fire, neighborhoods of oaks may avoid shoot mortality from high temperature and recruit to size classes sufficiently large (>10 cm dbh) so that they can survive low-intensity fire. In fact, a relatively short fire-free period, at stand or intra-stand scales, may be sufficient time for oaks to reach a size threshold for shoots to survive typical temperatures of prescribed fires. Where fire frequency is greater than three years and overstory density is low enough to permit >50% of full sunlight in the understory, shortleaf pine can develop into large advance reproduction, much like oak; and they will have increased competitive capacity after an overstory disturbance that releases regeneration. Another pathway to pine regeneration is in the presence of recurring fires after overstory removal. Pines develop thick bark more rapidly than hardwoods and can achieve resistance to topkill at an earlier age. Hence, if fires occur after pine reproduction reaches fire-tolerant size, it will discriminate against hardwood competitors [13, 14].

Figure 6.3 In natural, old pine-oak mixedwoods of the southeastern United States, pines often occur as clusters (i.e. pine-dominated neighborhoods) in what are otherwise oak-dominated stands.

6.3.5 Old Forest Stage

In older, natural mixed pine-oak systems, the pine component is often spatially clustered within the stand (Figure 6.3). The clustering of pine into distinct neighborhoods may result from stochastic events or biophysical site conditions [15]. For example, large canopy openings on xeric sites or those subjected to frequent, low-intensity fire may provide regeneration sites for pines. In the absence of stand-wide catastrophic disturbance, pine-oak stands may develop uneven-aged structures. Although the hardwood canopy component may represent a single age class, the pine component may represent multiple cohorts that established in accord with intra-stand scale canopy disturbances. Of course, these stands can be composed of multiple oak cohorts as well, as old pine-dominated neighborhoods succeed in oak dominance. Older stands are characterized by large living stems as well as large snags and downed logs. Pit and mound microtopography is common from windthrow and spatial patterns of species composition within stands (i.e. pine neighborhoods, oak neighborhoods) are often apparent.

6.4 Ecological Silvicultural Systems for Pine-Oak Ecosystems

The silvicultural approach used to create and/or maintain pine-oak stands depends principally upon the current prevailing condition (Table 6.2). Managers that wish to create pine-oak stands typically begin with pine stands, including pine plantations, that lack an oak component or oak stands that lack a pine component. Clearly, different silvicultural systems are required based on initial stand composition and structure. In both instances, an ecological silvicultural system based on natural development would likely begin in the young to mature forest stages. As stated above, the canopy disturbances that lead to regeneration and legacy creation in pine-oak systems often occur at intra-stand scales (Table 6.3). Thus, preforest and young forest stages may occur in neighborhoods within mature and old stands.

Table 6.2 An ecological silvicultural system for mixed pine-oak ecosystems during early stages of development based on initial stand conditions.

	Initial condition					
	Pine dominated		Oak dominated		Mixed pine-oak	
Stage	Potential actions	Outcome	Potential actions	Outcome	Potential actions	Outcome
Disturbance and legacy creation (0 y)	Variable-density thinning	Release oak advance reproduction	Patch clearcut with reserves	Create canopy openings for pine regeneration	Patch clearcut with reserves; Patch seedtree with reserves; Patch shelterwood with reserves	Create canopy openings for pine and oak regeneration
	Girdle and fell trees	Creation of dead downwood and snags	Girdle and fell trees	Creation of dead downwood and snags	Girdle and fell trees	Creation of dead downwood and snags
	Prescribed fire	Expose bare mineral soil; reduce competition from fire-sensitive species	Prescribed fire	Expose bare mineral soil; reduce competition from fire-sensitive species	Prescribed fire	Expose bare mineral soil; reduce competition from fire-sensitive species
Preforest (1+ y)	Chemical or mechanical competition control if needed	Reduce competition from shade-tolerant/fire-sensitive species	Outplant pine in canopy openings	Establish a pine cohort	Cluster plant pine seedlings if needed	Supplement natural pine regeneration in openings
					Chemical or mechanical competition control if needed	Reduce competition from shade-tolerant/fire-sensitive species
Young forest (1–80 y)	Prescribed fire	Expose bare mineral soil; reduce competition from fire-sensitive species	Prescribed fire	Expose bare mineral soil; reduce competition from fire-sensitive species	Prescribed fire	Expose bare mineral soil; reduce competition from fire-sensitive species
			Crop tree release pine as needed	Recruit pine individuals to the canopy		

Table 6.3 An ecological silvicultural system for mixed pine-oak ecosystems during mature and old forest stages.

Stage	Potential actions	Outcome
Mature forest (80–150 y)	Patch clearcut with reserves; patch seedtree with reserves; patch shelterwood with reserves	Regeneration of desired species in patches
	Cluster plant pine as needed in canopy openings	Supplement natural pine regeneration if required
	Prescribed fire	Reduce competition from fire-sensitive species; expose bare mineral soil
Old forest (150+ y)	Patch clearcut with reserves; patch seedtree with reserves; patch shelterwood with reserves	Regeneration of desired species in patches
	Cluster plant pine as needed in canopy openings	Supplement natural pine regeneration if required
	Prescribed fire	Reduce competition from fire-sensitive species; expose bare mineral soil

6.4.1 Disturbance and Legacy Creation

An ecological silvicultural system to convert pine stands, including pine plantations, into mixed pine-oak forests would take advantage of the developing hardwood understory. Oaks are often present in pine stands along with a diversity of other hardwoods. Red maple, a shade-tolerant species, is common and often dominant in pine understories and is a major competitor of oak. If oak advance reproduction is present, a localized, partial removal cutting may be used to thin the pine canopy and recruit oaks to larger size classes and eventually result in a two-aged stand. Thinning alone also releases other hardwoods in the understory including highly competitive red maple. If not controlled by prescribed fire or herbicide, red maple may dominate the future overstory.

Variable-density thinning (see Chapter 1) and group selection with reserves may be modeled after natural canopy disturbances. Intermediate-severity disturbances provide an appropriate template as these types of events may remove trees individually throughout a stand or in variably sized and shaped patches [8, 16]. The return interval of intermediate-severity disturbances is typically 20–50 years and provides a template for repeated stand entries. The long-term focus should be on maintaining a strong pine component. A shelterwood with reserves approach would work to recruit oak but may diminish the pine component so that long-term maintenance of pine in the stand could be a challenge. Larger pine trees would be retained in such a system as they would represent a key source of mature tree structure and future seed sources.

In oak stands that lack a strong pine component, a silvicultural system modeled after natural disturbance and development patterns may include patch clearcut or group selection with reserves. In existing pine-oak stands, an ecological silvicultural system may include seedtrees with reserves and shelterwood harvesting with different configurations of reserve tree spatial patterns. Combinations of regeneration methods may be used in large stands to account for initial stand conditions, variations in abiotic conditions, and other factors influencing regeneration such as invasive species, deer herbivory, and interfering ground flora. The sizes and shapes of the patches should be variable to account for the range of openings created by natural canopy disturbance events and to create the resource environment needed for regeneration of desired species (Figure 6.4). For example, wind disturbance often creates relatively small patches of less than 5 ha,

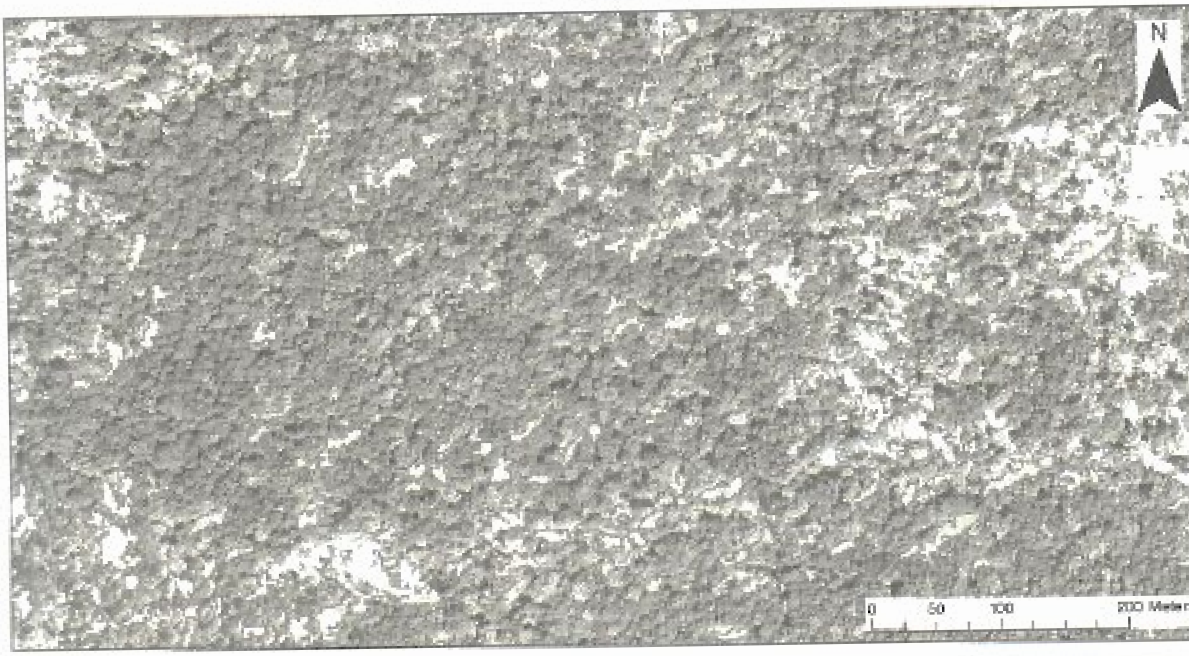

Figure 6.4 The size and shape of natural, intermediate-severity canopy disturbances are highly variable in pine-oak mixedwoods and these disturbances provide a template for silvicultural systems. In this image, natural canopy disturbance openings greater than 100 m^2 are highlighted.

however, these storms may also result in a low frequency of large openings of over 100 ha [17]. The shapes of natural canopy disturbances are also variable and range from circular openings to linear patterns [8]. The openings should be focused on microsites best suited for pine dominance, such as ridgelines and upper slope positions, south aspects, or other sites with convex curvature and soils where pine is inherently more competitive. In contrast, microsites such as fens, seeps, and springs that contain sensitive species or abiotic features may be avoided.

6.4.2 Preforest Stage

In pure hardwood stands, the pine component must be artificially regenerated in the harvest-created openings. Regardless, if regeneration is natural or artificial, site preparation is important and would normally include prescribed fire to reduce deep litter and competing vegetation. Herbicide may be required to reduce competition from hardwood stems. Site preparation treatments should be tailored based on site conditions and the specific pine species of interest. In harvest-created openings, outplanting of containerized shortleaf pine seedlings has been shown to achieve greater growth and survival compared to bare root seedlings, especially on nutrient-poor and dry sites [18]. In harvest openings, shortleaf pine seedlings may be planted at high densities (e.g. $<1 \times 1$ m; [19]). Newly planted pine seedlings are vulnerable to fire until they are established for a couple of years in adequate light environments. Thus, fire may be withheld until shortleaf pine seedlings reach a diameter of 2–10 cm [13] and height of 4–5 m [20] to reduce risk of topkill. If prescribed fire must be used to control competing vegetation, a three to five-year burn cycle maybe used to develop vigorous shortleaf pine sprout reproduction. Dey and Hartman [14] found that new shortleaf pine seedlings and advance reproduction of small basal diameter had a lower probability of survival after fire compared to hardwoods of similar size. Chemical treatment of hardwood competition may be necessary to increase height and diameter growth of planted shortleaf pine and could be used in conjunction with prescribed fire to decrease fire-induced mortality of shortleaf pine by reducing competing vegetation and potential fuel.

6.4.3 Young Forest Stage

Low-intensity surface fire is an important component of the disturbance regime in pine-oak stands and thus, a prescribed fire program is important in the young forest stage. Prescribed fire may be withheld until tree reproduction reaches size thresholds so that fire-related damage will be insignificant as discussed above. Tending of young regeneration and crop tree release at canopy closure may be needed to sustain pine in dominant crown positions to ensure desirable pine stocking levels.

6.4.4 Mature Forest Stage

In mature pine stands, prescribed fire can be used effectively either alone or in combination with overstory harvesting and other silvicultural practices to control the composition and development of hardwood regeneration in pine stand understories and promote oak dominance. Low-intensity dormant season fires can reduce midstory density by topkilling small hardwood stems, but typically increase the density of regeneration-sized stems due to sprouting of fire-injured midstory trees [21]. However, repeated fires over a decade can substantially reduce stem density, especially in the understory of fully-stocked, unthinned overstories [22]. Schweitzer et al. [23] reported that the hardwood midstory was largely eliminated by repeated burning and hardwood regeneration was greater with a heavy pine thinning, leaving 11 m^2 ha^{-1} of basal area, after three prescribed fires over nine years compared to less intense treatments. They found that thinning and repeated burning did favor development of larger oak reproduction, but the initially dominant red maple advance reproduction was still equally or more dense and larger than oak regeneration. Red maple is a prolific sprouter following the death of the shoot and its tolerance to shade allows it to recover between fires under moderate overstory densities.

In pure pine stands devoid of natural oak regeneration, oaks must be artificially regenerated by underplanting. Guidelines for success in oak plantings have been published (e.g. [24–26]). However, oak advance reproduction typically exists in mature pine stands in this region.

A common approach to establish a pine component in a mature oak stand is to prepare the site with prescribed fire to reduce woody competition, which may require multiple burns. The stand would then be thinned to increase light in the regeneration layer sufficient for pine survival and growth, and then pine seedlings would be underplanted. Further reductions in overstory density may be done around pockets of pine reproduction. Hardwood competition around individual pines or patches of pine reproduction can be controlled by mechanical or chemical thinning to release pine and promote its recruitment into the overstory. This approach however is not based on natural development patterns (i.e. hardwoods normally do not naturally stratify above pines) and typically treats stands uniformly without regard for the spatial patterns that are often apparent in old pine-oak stands.

In mature oak-dominated stands that have a minor pine component, silvicultural treatments may be used to increase pine dominance. For example, group seedtree harvests may be used to regenerate pine around existing sexually mature pine stems. In these situations, prescribed fire is important to expose bare mineral soil and reduce competition. Pine seed crops are episodic and operations may be timed to coincide with good seed production events. Even when mature pine trees exist on the site, supplemental planting of spots may be used to increase pine seedling density in openings. In general, we recommend focusing on the pine-dominated neighborhoods within stands instead of treating entire stands uniformly. Pine-dominated neighborhoods can be expanded with future entries. Subsequent treatments may create openings tangentially or concentrically to pine neighborhoods to expand neighborhood size.

6.4.5 Old Forest Stage

To account for inherent spatial patterns of species composition and structure typical in old pine-oak stands, we suggest that silvicultural systems use an approach that acknowledges spatial aspects of tree composition and that creates conditions that meet the silvical needs of the desired species without unduly promoting competition. Regeneration harvests will be essential in old pine-oak stands to ensure pine is regenerated and maintained in the system. Thus, disturbance and legacy creation at appropriate spatiotemporal scales is crucial to perpetuate old pine-oak stand conditions. We suggest harvest entries focus on intra-stand spatial patterns. For example, individual openings may range from 0.5 to 1 ha and be clustered at distances up to 200 m in groups of 2–5 openings [16]. We suggest these openings should contain reserve trees and these entries should occur at 20–50 year intervals based on the frequency of natural canopy disturbances. During entries, ecologically important features, such as large snags and large and emergent trees, should be retained. The long-term focus in old pine-oak stands must be on maintaining the pine component. The maintenance of mature pine trees for seed production and a prescribed fire program to enhance pine regeneration potential are critical. Fire effects are important to increase pine regeneration potential by exposing bare mineral soil and reducing hardwood competition.

6.5 Climate Change Considerations

In the southern United States, temperature is expected to increase, and droughts are projected to become more frequent and severe. Atmospheric disturbances that may result in catastrophic forest damage are expected to become more common. Pine-oak stands, because of their relatively diverse species assemblages and complex structures, should be more resistant and resilient to these perturbations and stressors, as some species may be better adapted to future climate conditions. Forest communities with high species diversity represent a wide range of life history strategies and functional traits. As plant species diversity increases, so does the probability that resident species have resistance to or will recover quickly from a perturbation. Promoting pine-oak mixedwoods increases stand diversity and landscape diversity in forested regions that are dominated by mature fully-stocked hardwood forests or monoculture pine plantations. Tree resistance to drought may be enhanced by reducing stand density such as in fire-maintained savannas and woodlands [27] and reducing stand density by thinning to retain drought-tolerant pines and oaks may increase resistance and recovery to drought [28]. Mixedwoods of pine and oak produce highly flammable litter and promote the return of a frequent fire regime. Fire-maintained mixedwoods should be well adapted to fire disturbances, which are expected to increase in the future.

6.6 Summary

Key points to consider based on natural disturbance and development patterns in pine-oak ecosystems include:

1) Intra-stand spatial variability of the species assemblage should be acknowledged. In old, natural pine-oak ecosystems, neighborhood-scale patterns of species composition and stand structure are often apparent.

2) Silvicultural systems that do not treat stands uniformly acknowledge intra-stand variability and would be consistent with natural patterns of disturbance in pine-oak ecosystems.
3) A silvicultural system modeled after natural disturbance and development patterns in pine-oak stands may include patch clearcut, seedtree, and shelterwood harvests with reserves, as well as variable-density thinning. These systems allow for selections based on spatial patterns of species assemblages and microsite variability within stands. These systems also result in multi-aged stands and relatively complex structures at the stand scale.
4) Prescribed fire is critical to create and maintain pine-oak ecosystems in promoting desired regeneration, managing competing vegetation, and modifying vegetation structure.
5) Prescribed fire application should be adjusted according to stand developmental processes and management goals. Prescribed fire should not be strictly implemented at a regular interval but, should be applied deliberately as needed in accordance with stand developmental processes and the silvics of desired species to achieve desired fire effects.
6) Regardless of the initial stand condition, the long-term focus of pine-oak ecosystem management should be on maintaining a pine component. Pine regeneration and recruitment is the bottleneck in mixedwood management.
7) Pine-oak ecosystems contain taxa with a wide range of life history and functional traits and are structurally complex, which confer enhanced ecosystem adaptation potential.

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