

RESTORATION OF TEMPERATE SAVANNAS AND WOODLANDS

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Introduction

Savannas and woodlands are open forest phases that occur along a gradient between grasslands and closed canopy forests. These ecosystems are characterized by open to nearly closed canopies of overstorey trees, relatively sparse midstorey and understorey woody vegetation, and dense, species-rich ground flora. In contrast to closed forests, the dominant and codominant trees in the canopy of open forests often have large, spreading crowns. Relatively open structure allows light to the floor, which is critical for grasses and forbs; the greatest plant species diversity and turnover rates occur in the herbaceous layer of open forest ecosystems in temperate zones (Gilliam 2007). Open structure, old trees, and variation of light and microclimate are important for lichens (Paltto *et al.* 2011), insects (e.g. carabids; Taboada *et al.* 2011), birds (Hunter *et al.* 2001), mammals and other taxa.

Savannas and woodlands result from low severity disturbances or conditions that restrict development of dense forests with closed canopies. Type and severity of disturbance vary according to region and temporally. In North America, low-severity fire, resulting from lightning or deliberate ignitions, historically prevented closed forest development, although forests also may be limited by grazing and browsing, land use practices, shallow soils, or drought. Large diameter fire-tolerant tree species survive surface fire, while herbaceous vegetation is favoured by fire compared to shrubs, small-diameter trees, and other woody vegetation that lose a considerable proportion of their energy reserves if their aboveground tissue is consumed (Brose *et al.* 2013). Tree species and other vegetation adapted to surface fire regimes often produce fine fuels to promote fire spread through litter that dries rapidly and decomposes slowly. Due to fire exclusion that began during the mid-1800s to mid-1900s, in combination with extensive harvest and land use conversion, most open forest ecosystems in North America have transitioned to closed forests that support a different suite of species than open forests. A combination of large herbivores, fire, and climate may have been important in maintaining the open woodland structure of Europe, while silvopastoralism and transhumance shepherding (e.g. seasonal movement) that often entail practices such as coppicing, pollarding, and grazing currently maintain wood-pastures (Vera 2000; Sandom *et al.* 2014; Plieninger *et al.* 2015).

In this chapter, we will describe state of the art restoration techniques for open forest ecosystems that once occurred across large areas in North America (Figure 11.1) and Europe, using

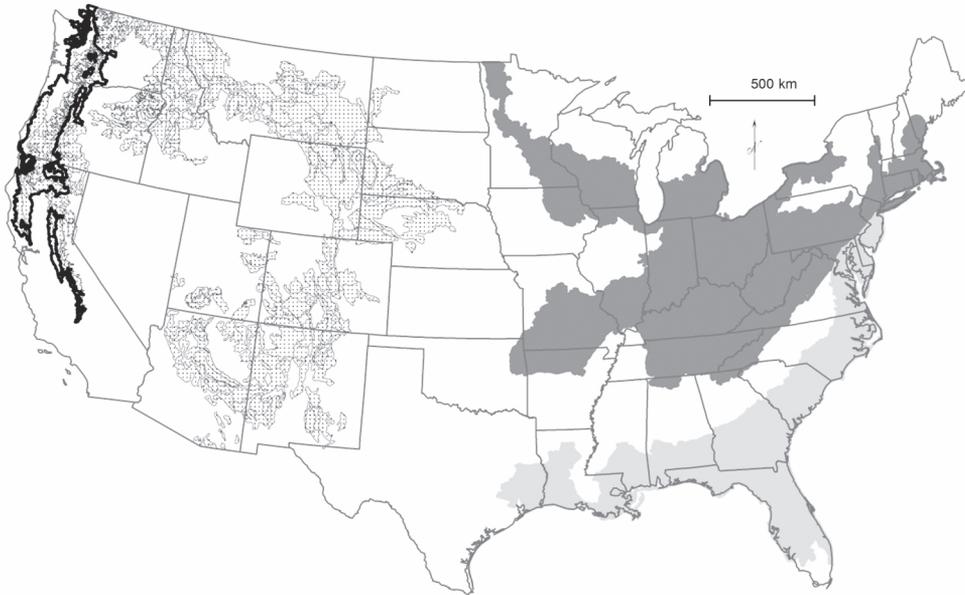


Figure 11.1 Eastern oak savannas and woodlands occurred in the central eastern United States (shaded dark grey), longleaf pine in the southern Coastal Plain (shaded light grey), ponderosa pine throughout the western United States (stippled), and Garry oak in the Pacific Northwest and into California (dark outline)

a broad, systematic approach to address the complex issue of open woodlands for two continents. Savannas and woodlands are described in North America, Europe and portions of Australia, where synonyms include barrens and parklands in North America and wood-pastures in Europe. Savannas and woodlands are poorly described in temperate Asia, South America and Africa but appear to occur in localized areas within grassland ecosystems of steppes, pampas and veld. For North America, the structural threshold that separates temperate savannas from woodlands may vary regionally, but we recently suggested a maximum of 30 per cent stocking (or growing space occupied; Figure 11.2) and 100 trees ha^{-1} ≥ 12.7 cm diameter, with about 40–50 per cent canopy closure; the threshold between woodland and forest is approximately 75 per cent stocking and 250 trees ha^{-1} and more importantly, an open midstorey (Hanberry *et al.* 2014). For Europe, the crucial defining feature for wood-pasture systems is presence of grazing, which produces tree densities ranging from 10–100 ha^{-1} for oak wood-pastures to 200–500 trees ha^{-1} in some sub-alpine wood-pastures (Hartel *et al.* 2013; Garbarino and Bergmeier 2014). Despite variation, we suggest that the primary concern is restoration of the open forested state; in general, management of a greater area of open woodlands rather than a smaller area of savannas surrounded by closed forests will provide a greater return in terms of support of declining species and rare ecosystems.

Representative North American savannas and woodlands

Oaks were the dominant species of savannas and woodlands that historically covered large landscapes in the central eastern United States, particularly along the western side of eastern forests

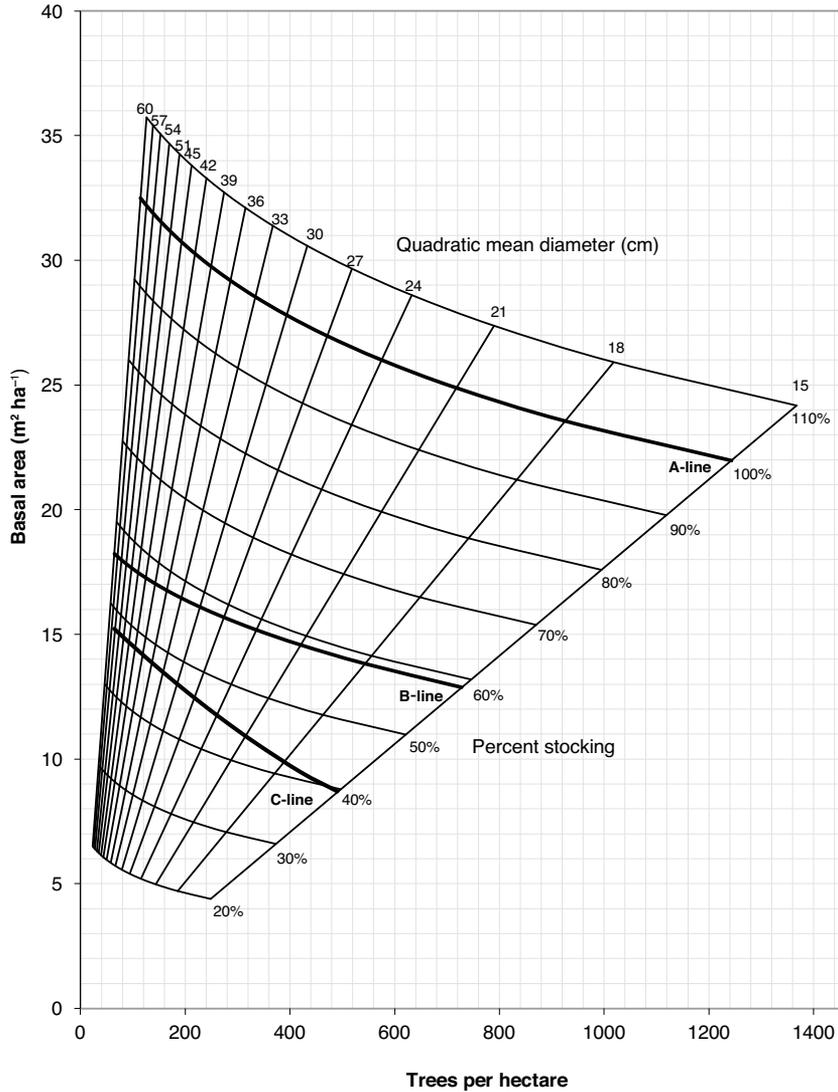


Figure 11.2 Stocking chart (Gingrich 1967) for oaks and hickories where the quadratic mean diameter at breast height is >18 cm. Maintenance operations in woodlands keep the stocking between 30 and 75 per cent stocking with ‘closed-canopy’ woodlands maintained near the B line and ‘open-canopy’ woodlands maintained below the B line. At stocking levels less than 30 to 35 per cent the structure begins to resemble that of a savanna. For regenerating woodlands, stocking is reduced below the C line. The stocking chart can be used to convert stocking levels to a basal-area basis for managements units of a given average diameter

and on dry and nutrient-deficient sites that supported lower plant densities and slower growth (Kabrick *et al.* 2008; Figure 11.1). Generally, white oak (*Quercus alba*) was common along with black (*Q. velutina*), post (*Q. stellata*), chestnut (*Q. montana*), northern red (*Q. rubra*), blackjack (*Q. marilandica*), and bur (*Q. macrocarpa*) oaks, varying by location. Frequent surface fire

maintained fire-tolerant oak species. Cotyledons of oak seedlings are belowground; if top-killed by fire, the cotyledons remain protected and provide some of the nourishment needed to resprout and remain in the stand. Oak seedlings also establish a large root system at the expense of early shoot growth. This larger root system enables oak seedlings to resprout readily after being top-killed. Numerous ground flora species are considered woodland indicators, particularly graminoids, sedges, and forb species in the genera *Lespedeza*, *Silphium*, *Solidago* and *Symphytotrichum*. Most woodland indicator species are herbaceous plants that produce flowers and seeds during the summer months and are adapted to ecosystems where light penetration is relatively high. Open oak forest ecosystems have transitioned to closed broadleaf forests composed of a variety of tree species, without frequent low severity surface fires that favoured oak species and non-woody plants.

Much of the southeastern United States historically was dominated by longleaf pine (*Pinus palustris*) savannas and woodlands, occupying an estimated 37 million hectares within the Coastal Plain, the fall-line sandhills, and mountains of central Georgia and Alabama. Longleaf pine trees can regenerate and recruit under fire return intervals of 2–3 years due to adaptations to frequent, low severity fire. Longleaf pine seedlings develop a large root system while delaying height growth in their unique grass stage, and seedlings begin height growth when the root collar diameter is approximately 2.5 cm, at which point the cambium is protected by exceptionally thick bark. Frequent fire promotes the development of herbaceous ground flora, including bunchgrasses such as wiregrass (*Aristida* spp.) or bluestems (*Andropogon* spp., *Schizachyrium* spp.), which creates a positive feedback by contributing fine fuels for subsequent fires (Mitchell *et al.* 2009).

In the Pacific Northwest, drier areas in the lowlands of western Oregon, Washington, and coastal British Columbia historically supported extensive savannas and woodlands, largely defined by Garry oaks (*Quercus garryana*; Oregon white oak). Regular burning by Native Americans limited regeneration and growth of Douglas-fir (*Pseudotsuga menziesii*) and other rapidly-growing, taller conifers. Today, oak woodlands have been reduced to a few per cent of their historical extent. Douglas-firs have overtopped the oak canopy in many areas and understories have become dense thickets of native and exotic shrubs, particularly Himalayan blackberry (*Rubus armeniacus*) and Scotch broom (*Cytisus scoparius*), often resulting in the loss of ground flora.

Ponderosa pine savannas and woodlands cover approximately 1.6 million hectares that are dispersed across the western United States (McPherson 1997). These ecosystems experience periods of high temperatures with little or no precipitation causing plant stress (*ibid.*). Fire, by lightning and deliberate ignition, was the primary disturbance that sustained pine savannas. Since European settlement, overgrazing, fire exclusion, species introductions, and some timber harvesting changed ponderosa pine savannas (Jain *et al.* 2012). Between the mid-1800s through early 1900s, overgrazing by cattle, sheep, and horses promoted the spread of invasive plants that were introduced during settlement and compacted soil, resulting in reduced water infiltration and increased erosion, and ultimately changed plant community species composition and diversity (Belsky and Blumenthal 1997).

European wood-pastures

Wood-pastures in the European Union cover approximately 203,000 km², out of which approximately 109,000 km² are pastures with sparse trees (i.e. the typical 'savanna' type of landscape), 85,000 km² are pastures in open woodlands, and 9000 km² are pastures with cultivated trees (e.g. olive groves and fruit trees; Plieninger *et al.* 2015). Spain, Romania, and Portugal have

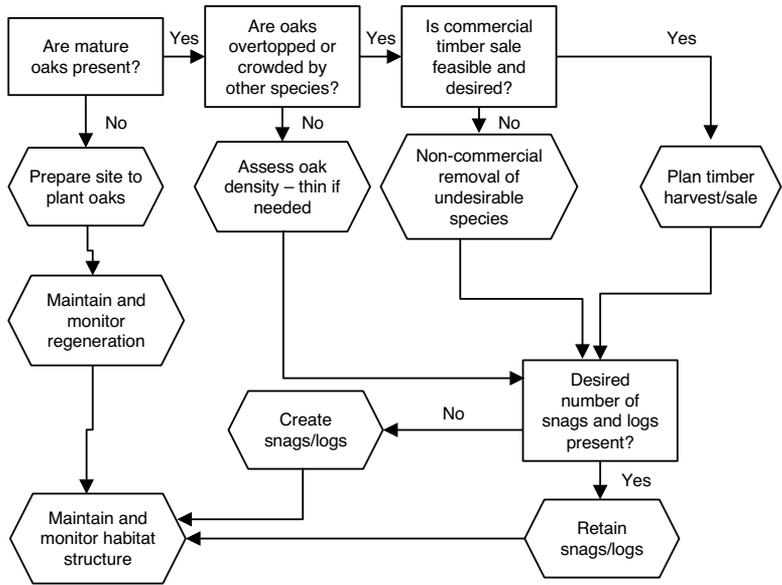
the greatest coverage of wood-pastures and retain the most traditional land-use practices. Wood-pastures in the temperate and submeridional broadleaved woodlands (following Bergmeier *et al.* 2010) region contain a diversity of dominant tree species, including oaks (e.g. *Q. robur*, *Q. petraea*, *Q. pyrenaica*, *Q. pubescens*, *Q. fainetto*, *Q. cerris*, *Q. suber*) but also species such as *Carpinus betulus*, *Fagus sylvatica*, *Ulmus* spp., and a number of coniferous trees in the mountainous areas (e.g. *Pinus sylvestris*, *Abies alba*, *A. pinsapo*). Grazing livestock include cattle, buffalo, pig, horses, sheep, and goats (Bergmeier *et al.* 2010). Southern European wood-pastures are dominated by more xerophyllous trees and shrubs. Sheep use is common in Spanish transhumance, and grazing may prevent fire in these ecosystems. Traditional grazing systems have changed in the majority of countries to become more intensive and without seasonal movement. Additionally, with the exception of cork production, wood and other tree products are rarely extracted from pastures; coppicing (cutting the stems at the basal level while allowing multiple stems to regenerate from the stump for harvest again in roughly 7 to 30 year cycles) and pollarding (applying the same intervention above the browsing height of the livestock) have been largely abandoned (Hartel *et al.* 2015) for modern silvicultural practices that produce timber and other forest products.

General restoration guidelines

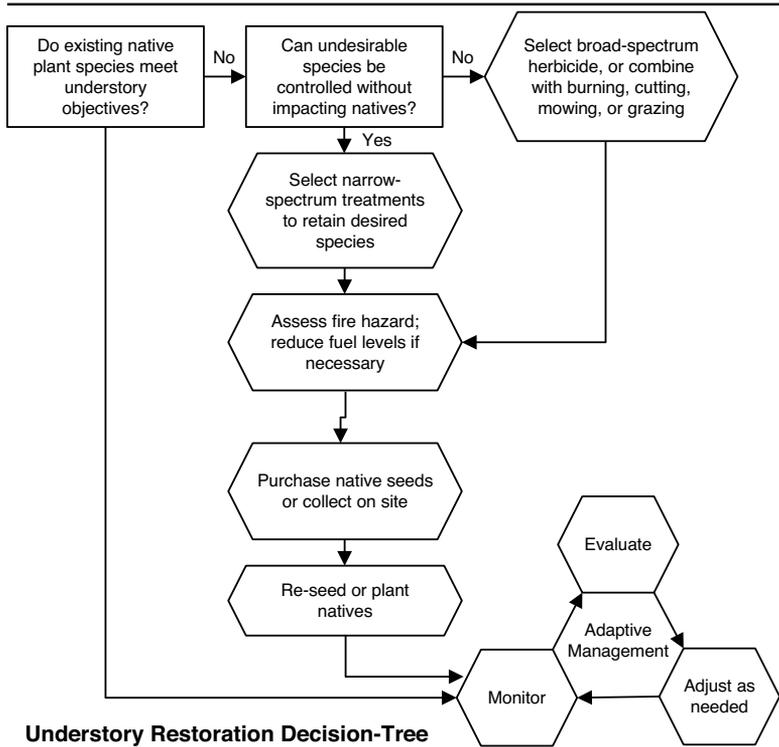
First and foremost, clear and specific objectives are necessary for a restoration prescription that includes information about current condition, desired future condition, and social and economic context for the area planned for restoration. With clear objectives defined, identification of treatment and potential treatment combinations, timing of application, and proposed vegetative target thresholds or indicators (i.e. establishment of preferred species) is most efficient (Figures 11.3 and 11.4). Additionally, monitoring to determine management effectiveness will guide future decisions (i.e. adaptive management) and identify when a maintenance treatment is needed to sustain the ecosystem.

An inventory of tree composition and density, ground flora, and soil is essential to assess restoration and management potential (Table 11.1). Sites with the greatest restoration potential already contain tree species of interest in the overstorey. Presence of woodland indicator ground flora, which are a critical component to restoration and also provide fuel for frequent surface fires, is a valuable additional element that often is absent or highly depauperate. Low abundance or richness of woodland ground flora may indicate that the site has been eroded, grazed severely, ploughed, or has remained for many decades in a closed canopy state, although viable seeds and bulbs of understorey taxa may be present in the soil seedbank. Information about native vegetation may be included in a soil survey or plant associations (Peet 2006), and management units can be grouped using similar soils and stand conditions. Soils, terrain, and precipitation must support desired changes and match the desired plant species. In some regions, selection of certain topography and soils will make restoration more successful by reducing competition from other species. Indicators of historical wood-pastures in Europe are presence of:

- large trees (e.g. veteran pedunculate oaks);
- large herbivores;
- open woodland communities;
- archaeological features typical of wood-pastures;
- historical records and maps; and
- oral history (Kirby and Perry 2014).



Overstory Restoration Decision-Tree



Understory Restoration Decision-Tree

Figure 11.3 Decision trees for overstorey and understory restoration in oak savannas and woodlands of the Pacific Northwest

Source: adapted from Vesely and Tucker (2004)

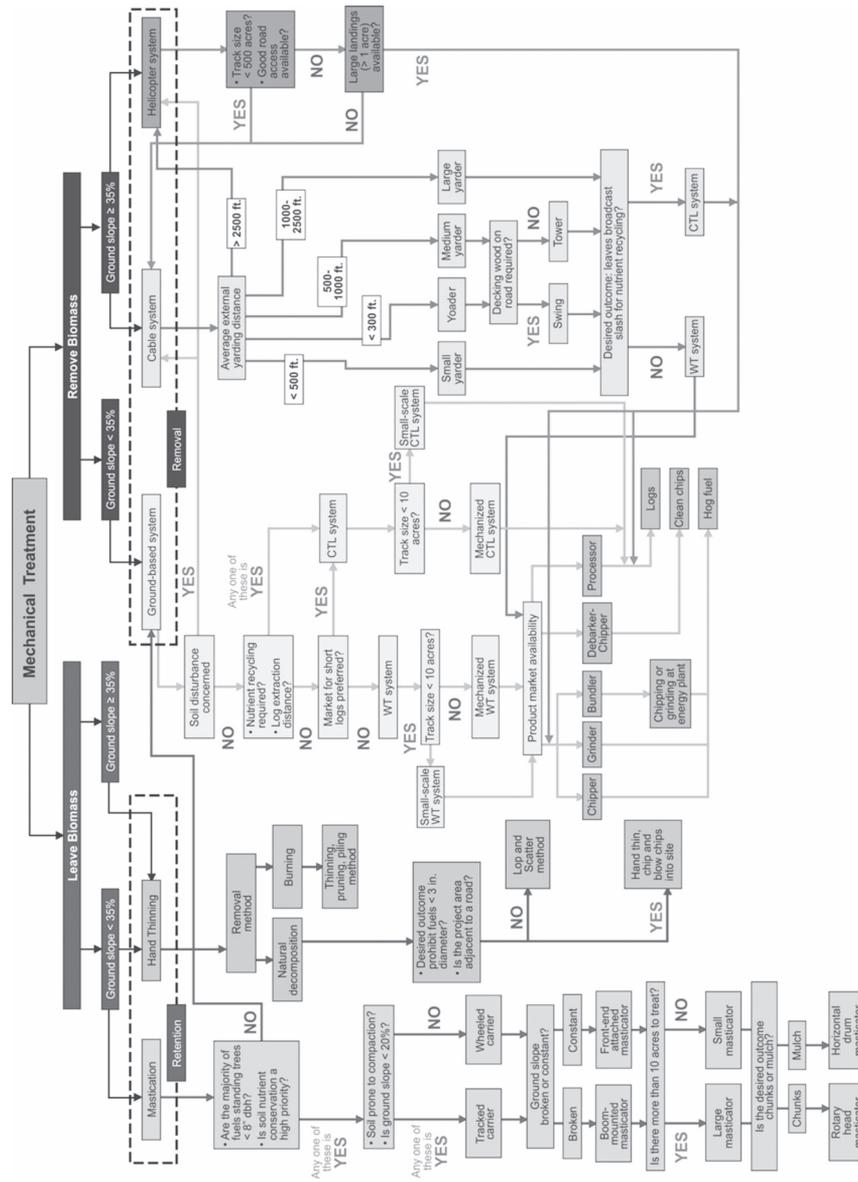


Figure 11.4 Decision tree for equipment selection during restoration of ponderosa pine in the western United States. Equipment selection should fulfil treatment objectives, work conditions under which treatment operations are implemented, and efficient use of limited budget

Source: adapted from Jain *et al.* (2012)

Table 11.1 Example inventory for managing woodlands and savannas in the eastern United States

Stand or mgt. unit	Soil series	Slope position	AWC (cm)	pH	Ecological site description	Tree density (ha ⁻¹)	Basal area (m ² ha ⁻¹)	Stocking (Gingrich 1967)	Dominant tree species	Woodland indicators present
1	Nixa-Clarksville Complex, 1–3% slopes	Summits	17.8	5.0	Quercus stellata– Quercus velutina/ Amelanchier arborea– Vaccinium pallidum/ Helianthus hirsutus– Schizachyrium scoparium	951	18.9	87	Quercus alba, Quercus velutina, Quercus stellata	Helianthus hirsutus, Parthenium integrifolium
2	Coulstone- Clarksville complex, 3 to 8% slopes	Summits and shoulders	19.6	5.0	Quercus velutina– Pinus echinata/ Rhus aromatica– Vaccinium pallidum/ Carex–Schizachyrium scoparium	1119	22.3	99	Quercus alba, Quercus velutina, Quercus coccinea	Lespedeza hirta, Tephrosia virginiana
3	Clarksville very gravelly silt loam, 35 to 50% slopes, very stony	East-facing backslopes	18.3	5.0	Quercus stellata– Pinus echinata/ Vaccinium arboreum Schizachyrium scoparium– Desmodium	894	18.6	83	Quercus alba, Quercus velutina, Quercus stellata	Vaccinium arboretum, Desmodium rotundifolium
4	Leon fine sand, very deep, poorly drained, 0 to 2% slopes	Atlantic Coastal Plain flatwoods	10.2	5.1	Pinus palustris– Pinus serotina/ Gaylussacia dumosa/ Vaccinium crassifolium– Aristida stricta Woodland	222	23.0		Pinus taeda	Aristida stricta, Gaylussacia dumosa
5	Nankin sandy loam, very deep, well drained, 5 to 12% slopes	Eastern Gulf Coastal Plain	20.1	5.0	Pinus palustris/ Schizachyrium scoparium/ Verbena aristata Loam-hill Woodland	371	27.6		Pinus taeda Quercus marilandica Quercus falcata	Schizachyrium scoparium Sericocarpus asteroides Solidago odora

Restoration and management of savannas and woodlands can be conceptualized as occurring in three different steps: restoration, maintenance, and recruitment. Stand conditions assessed in the inventory determine the initial step (Table 11.2). The restoration step applies when initiating management in woodlands where tree and shrub density is high or loss of species of interest has occurred. The maintenance step occurs where structure and composition of the tree canopy have been restored and treatments occur as needed to remove woody reproduction and enhance cover and diversity of ground flora. The recruitment step occurs when regeneration and recruitment of new trees is necessary or desirable. Lack of tree regeneration in wood-pastures is a commonly recognized threat in Europe (Bergmeier *et al.* 2010).

Vegetation can be removed through burning, mechanical, chemical, and grazing (or browsing) treatments. However, fire may be contraindicated without an ecological or cultural history, and fire and chemical use may be regulated. Significant change may require several years and multiple applications of one or more methods. Factors such as minimizing soil compaction, logistics, and topography may affect choices. Removing biomass may offset the cost of implementation if the biomass is a sellable product and infrastructure exists. Methods for vegetation removal can prepare sites for species reintroduction, but removal of one species may favour establishment of unwanted species; thus the surrounding area, potential seed sources, and time a site is susceptible to invasion also are important considerations.

Where current overstorey tree recruitment levels are insufficient, seedlings can be established by direct seeding or by planting bareroot or container stock seedlings. In many cases, overplanting will be necessary to allow for browsing mortality. Survival often can be enhanced by using tree shelters, cages, root guards, mulch, weed barrier cloth, and thorny shrubs to reduce browse and conserve water. Savanna and woodland restoration objectives for understorey communities are similar to grassland restoration. Fire and/or removal of dry biomass may be critical to stimulating germination of seeds in the seed bank. If planting or direct seeding is used, plants must be adapted to edaphic and climatic site conditions. Multi-species seed

Table 11.2 Management triggers and tools for oaks in the eastern United States

<i>Management step</i>	<i>Assessment tools</i>
When to initiate the restoration step	
Suitable site conditions	Soil survey, on-site investigation
Presence of mature overstorey trees	Stand examination
Overstorey stocking > 75%	Inventory and stocking chart
Woodland indicators present	Woodland indicator species list
Presence of deep litter	Stand examination
When to initiate the maintenance step	
Overstorey stocking < 75%	Inventory and stocking chart
Understorey sparse or absent	Stand examination
Woodland indicators abundant	Woodland indicator species list
When > three prescribed burns have been conducted	Management plan
When to initiate the recruitment step	
Stand exceeds designated rotation age	Management plan
Overstorey mortality is excessive	Stand examination
Desirable advance reproduction present	Reproduction survey

mixtures should be planted because they maintain diverse plant communities that are resilient to multiple disturbances, limit invasive plants, and enhance wildlife habitat. Select the seed mixture carefully for purity, viability, and similar competitive ability. Planting time is critical to ensure there is sufficient precipitation for establishment.

Restoration in North America

Eastern and western oaks

Restoration goals for canopy tree abundance in savannas and woodlands can be based on measures such as tree density, canopy cover, and stocking, which will differ by region and community type. In mature eastern woodlands with large diameter (>30 cm) trees, there will be about 75 to 300 canopy dominant or codominant trees ha⁻¹, which corresponds to a desirable stocking level for closed woodlands that ranges from 55 to 75 per cent and for open woodlands that ranges from 30 to 55 per cent. In the Pacific Northwest, Campbell (2004) has suggested a goal of 5–30 per cent canopy cover for savannas and 30–60 per cent for woodlands; Dunwiddie *et al.* (2011) reported a historical density of about 80 canopy dominant trees ha⁻¹ in a Garry oak/Douglas-fir woodland in Washington.

In stands with many small trees, higher stocking levels (55 to 70%) should be maintained until woody sprouts have been controlled by prescribed fire. Higher stocking levels will allow some light penetration to the forest floor but reduce the growth rate of woody understorey species. If release of small trees is not a concern or if the overstorey is capturing most of the light, or after control of small tree growth, then considerable thinning or girdling of canopy trees may be necessary (Harrington and Devine 2006). Mechanical or chemical thinning from below to remove the midstorey trees first, followed by canopy trees if necessary, will reduce stand density to an overall density or stocking appropriate to woodland or savanna restoration goals (see stocking chart; Figure 11.2). Unlike mechanical thinning, chemical thinning prevents trees from resprouting.

Prescribed fire and thinning treatments may be applied to reduce understorey and midstorey density and leaf litter accumulation, increasing sunlight to the ground. Initially, prescribed fire may not be possible before other treatments, due to loss of fine fuels or presence of shrubs that will increase fire intensity. Prescribed fire may be applied annually during this step but is more typically applied every other year or every three years to protect mineral soil and retain soil organic matter, which is needed for maintaining water infiltration and plant growth. Low intensity prescribed fires are sufficient for removing some leaf litter and killing aboveground growth of small trees but will have little effect on overstorey and midstorey trees. Higher intensity prescribed burns will remove more leaf litter and top kill (i.e. kill aboveground growth) shrubs and trees up to 25 cm in diameter, thereby reducing overall stand density by thinning from below. Growing season burns are more lethal to woody vegetation than dormant season burns although high humidity and green fuels can reduce the rate of spread or leave large areas unburned and are more difficult to conduct. Herbicide control of invasive species as well as extensive seeding of native species may be necessary.

After stand structure and ground flora objectives have been achieved through restoration treatments, management shifts in emphasis to monitoring and maintenance of structure and composition using prescribed fire and periodic thinning as needed. Prescribed fire can enhance ground flora and reduce woody plant density in the understorey and alter behaviour of subsequent prescribed fire. The shift from a fuel type dominated by leaf litter and seedlings to a fuel type dominated by forbs and grasses causes prescribed fire to burn with a greater flame length

and intensity and with a greater rate of spread. Prescribed fire intensity in this step needs to be based on consideration that younger and smaller trees are more susceptible to losses in commercial value when fire-scarred years prior to commercial harvests because of the longer period for decay to occur to damaged cambium. If higher levels of stocking are acceptable, then only prescribed fire needs to be applied to maintain an open midstorey.

The stocking level can be reduced through commercial harvesting if there is sufficient merchantable material to warrant a timber sale and if impacts from logging activities do not damage the understorey. Otherwise, non-commercial thinning from below can meet desired stocking levels. As a general rule, stocking will increase by about 1.3 per cent per year when reduced to below the B level (Figure 11.2). On good sites this may be as much as 3 per cent and on poor sites as low as 1 per cent (Dale and Hilt 1989). Woodlands thinned to 30 per cent stocking can be expected to reach canopy closure, or B-level stocking, in about 20 years. Maintaining variation in stocking throughout the woodland is desirable and stocking can be adjusted to different levels depending on local soil conditions and slope position.

During the recruitment step, reduction of overall stocking will release oak seedlings that have accumulated during the maintenance step. Where economically viable, commercial timber harvests should be conducted. Distribution of retained trees can be varied so that there are locations within the stand with large openings and other locations where trees remain and stocking is greater. Thinning from below is recommended and retained trees should be large-crowned pines and oaks that provide habitat for wildlife and are considered 'character' trees for the woodland. Additionally, partial shade provided by retained trees will reduce woody regrowth surrounding residual trees. Prescribed fire should be excluded until a portion of the reproduction cohort is sufficiently large to escape being top-killed by fire.

Southeastern pines

The restoration step in longleaf pine savannas and woodlands often focuses on establishing longleaf pine as a future canopy tree, reducing midstorey densities, improving ground flora composition and abundance, and perpetuating desirable characteristics of forest fuels. Because longleaf pine occurs in <3 per cent of its historic range, artificial regeneration commonly is required, and development of container-grown nursery seedlings has greatly improved survival of planted longleaf pine seedlings (South *et al.* 2005). Conventionally, artificial regeneration is preceded by harvesting existing canopy trees, but underplanting is possible in existing pine forests, after reducing canopy density to 5–11 m² ha⁻¹ basal area (Mitchell *et al.* 2006; Knapp *et al.* 2013).

Mechanical treatments, for example using rotary mowers or chainsaws, reduce midstorey densities and increase light to the forest floor but also result in resprouting. Herbicides such as hexazinone, imazapyr, or triclopyr may also be required to reduce woody stem density. Regardless of herbicides or mechanical treatments, prescribed fire is critical for restoring herbaceous ground flora and ecosystem function (Brockway *et al.* 2009; Martin and Kirkman 2009). Agricultural legacies present additional restoration challenges by changing ground flora composition and physical and chemical soil characteristics. Herbicides such as hexazinone and sulfometuron methyl may be needed to control non-desirable, 'old-field weeds' to improve longleaf pine seedling establishment (Ramsey *et al.* 2003). Many desirable, native ground flora species are long-lived perennials that are slow to recolonize following soil disturbance. If the seedbank is depleted, seeds of native species may be broadcast or nursery-grown plugs of native species may be planted throughout the restoration site.

In longleaf pine ecosystems, the maintenance and recruitment steps can occur simultaneously due to fire tolerance of longleaf pine seedlings and saplings. A frequent fire regime of 2–5

years generally is appropriate for limiting development of broadleaf trees, enhancing herbaceous ground flora, and allowing for longleaf pine regeneration and recruitment. Single-tree selection methods that also include removal of small groups of trees create heterogeneous forest structure that allows for spatially variable patterns of tree regeneration (Mitchell *et al.* 2006). Canopy openings of 0.1–0.25 ha are large enough to release longleaf pine seedlings into larger size classes. Woodland objectives are often compatible with extended rotation lengths, which provides habitat for wildlife specialists (e.g. the red-cockaded woodpecker) and can increase market opportunities for timber (e.g. telephone poles).

Western pines

Restoration of ponderosa pine savannas and woodlands requires removing unwanted woody vegetation and invasive species followed by restoring plant communities and function, including reintroducing disturbance (McPherson 1997). If prescribed fire is used to remove excess vegetation and enhance preferred species expansion, then experience, intuition, and uncertainty are part of the prescription because unique conditions will influence the outcome (Sackett *et al.* 1993, 1996). Nonetheless, success is dependent upon target tree size and species and fire intensity, which is a function of fuel load, relative humidity, daytime temperature, fuel moisture, soil heating, and rate of spread (Jain *et al.* 2012). The season affects plant life cycles and phenology at the time of prescribed fire, influencing post-fire community trajectory (Knapp *et al.* 2009; Kerns *et al.* 2006). If woody vegetation has increased surface litter and humus, harvest plus multiple prescribed fires may be necessary to return the forest floor to desired conditions. There are periods when wildlife cannot escape a fire (such as during birth and rearing), which can influence when prescribed fire is applied, but specific details about seasonality and impact are rare and often anecdotal (Pilliod *et al.* 2006; Knapp *et al.* 2009). For maintenance, varying time between prescribed fires reduces selection for certain species and increases potential for diversifying species composition (Knapp *et al.* 2009).

Chemical control generally is an effective way to remove invasive species and specific herbicides target a unique species or group of species. Desired vegetation must respond to release and the herbicide must match the species targeted for removal. Multiple applications may be needed to control sprouting species. Soil texture can decrease herbicide effectiveness; sandy soils may drain quickly while clayey or loamy soils can quickly immobilize a soil-active herbicide. Herbicides become impractical with large and tall vegetation. Vegetation does not die immediately and once dead, the stems potentially may create a fuel hazard. Costs of chemical methods will depend on acreage being treated, mode of application, and type and amount of herbicide.

In contrast to overgrazing, targeted grazing is a controlled approach to change species composition through herbivory. Success is dependent on matching the appropriate type of livestock to the targeted vegetation. Goats and other woody browsers are not useful for grass or invasive forb control. Use of multiple species over sequential periods and matching grazing period to when the target plant is most vulnerable will result in greatest benefit. For example, sheep consume flower heads of leafy spurge early in the year and cattle consume the plant during the grazing season (Burritt and Frost 2006).

Restoration of European wood-pastures

Large herbivores were important in management of wood-pastures in many parts of lowland Europe (Figure 11.5). Crucial aspects of use of large grazers (cattle, horse, and water buffalo)



Figure 11.5 Oak wood-pasture grazed traditionally by water buffalo, horse and cattle in Transylvania. Small sized ponds such as the one in the front, left side of the picture are crucial for water buffalo, which contribute to maintenance of these ponds. Moreover, these ponds are critical breeding habitats for the yellow-bellied toad, an endangered European amphibian

include herbivore selectivity for certain habitat types and plants, density and temporal variation of herbivores or grazing pressure (animal units, AU ha⁻¹ year⁻¹), trampling and seed dispersion by herbivores, various strategies of plants for coping with herbivores, existence of grazing refugia (where the grazing pressure decreases, at least temporarily), light requirements of plants, and nutrient content of the soil (Olf *et al.* 1999). A grazing pressure of approximately 0.20–0.50 AU ha⁻¹ generally allows tree regeneration in wood-pastures, but in some contexts, grazing pressure of 0.1–0.2 AU ha⁻¹ or even lower is preferable, particularly for lands enrolled in payment packages for environmentally friendly farming. At herbivore densities ≥ 0.5 ha⁻¹, woody vegetation will not regenerate outside of protective structures; grazing pressure in Oostvaardersplassen (5,600 ha, the largest and oldest rewilding area of Europe, situated in the Netherlands) is extremely high (currently approx. 2.6 AU ha⁻¹) and is formed by Heck cattle, Konik horses and red deer that are regulated by their own density; tree regeneration only occurs under protective structures in such conditions. A grazing rotation scheme where parts of the grazed woodlands are delineated and grazing temporarily is prohibited allows tree regeneration, similar to non-continuous grazing practices such as transhumance shepherding in Spain that allows oak regeneration in dehesas.

Coppicing and pollarding also contributed to the maintenance of open woodlands. Some trees are more responsive to coppicing and pollarding (e.g. *Quercus* spp., *Carpinus betulus*, *Fagus sylvatica*, *Fraxinus* spp., *Salix* spp., *Betula* spp.) while other trees are less responsive (e.g. coniferous

species lack basal buds). Coppicing now is considered a highly inefficient forestry practice for timber production. The economic output of coppices can be enhanced by lengthening the coppice rotation, selective crown thinning around the best formed individual stems, and clearing undergrowth and thinning to select best stems, creating an open silvopastoral woodland structure suitable for grazing by domestic animals (Buckley and Mills 2015).

Removal of (often shade-tolerant) trees to re-create open light conditions around large trees is called 'haloing'. Sudden release of overgrown trees potentially may affect trees and epiphytes by wind damage and water stress. Clearance in 2–3 operations over 10 years may be beneficial for oaks of at least 250 years if the oak is densely overgrown and immediate clearing (in one operation) when the oak is moderately overgrown (Johannesson and Elk 2005).

Challenges

Savannas and woodlands have a long history of low intensity disturbance and management. Cessation or intensification of disturbance and management will transform the ecosystems into either treeless grasslands or closed forests. Once changed, restoration of savannas and woodlands may take decades, even if canopy trees are present, and great financial investment. Restoration of savannas and woodlands is challenging because restoration typically requires removing unwanted vegetation, returning disturbance patterns (type, severity, frequency), and establishing desired tree and understorey species. Even with intervention, restoration is not guaranteed; therefore, it may be a better use of limited resources to first maintain existing savannas and woodlands. Each place, management period, and social-economic context is unique, thus no specific guidelines exist. However, clear and specific objectives (e.g. desired future condition within an ecological, social, and economic context) will guide restoration prescriptions, including tool selection, implementation period, and specific treatment parameters.

Immediate challenges include formal recognition of savannas and woodlands as multifunctional ecosystems where both trees and the herbaceous layer are critical for biodiversity. Low severity historical disturbance and management regimes produced open forest ecosystems rather than the current landscape pattern of closed forest and cleared land. Open forest ecosystems and clearcuts provide comparable habitat for many early-successional species and we suggest directing resources to maintenance and restoration of open forests, rather than creation of transient clearcuts that fragment forests. There is a need for closer collaboration between various institutional sectors (such as forestry and agriculture) to find economic incentives for multifunctional low intensity use of savannas and woodlands. While economic returns from grazing are great enough to maintain (or often intensify) grazing, maintenance of open forests by mechanical harvesting often is unprofitable.

We have hope in finding resources to restore a frequent, low intensity disturbance regime in some areas even as we recognize that disturbances have changed over the last 100 years and will continue to change into the future. We know that people who recognize historical ecosystems have, in some cases, written them off as having no place under current and developing stressors. However, current and coming environmental changes may provide reasons to restore rather than challenges to the need for restoration. For example, increasing aridity due to climate change in some areas are likely to generate conditions that favour savannas and woodlands over closed forests. Restoration, if done well, increases biodiversity and a variety of ecosystem services; therefore, forest management and restoration share principles of maintaining biodiversity, structure, and function that prepare forests for an uncertain future (Hanberry *et al.* 2015). It is easier to devalue restoration of ecosystems that historically were widespread than to commit to restoration of open forest ecosystems and diverse species associated with open forests.

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