# *chapter eleven*

# *Cultural practices for restoring and maintaining ecosystem function*

**David H. Van Lear**
*Clemson University*
**Tricia L. Wurtz**
*US Department of Agriculture Forest Service*

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## *11.1 Introduction*

Forest restoration, in a general sense, suggests a transition from a degraded state to some "natural" condition, presumably devoid of human influence (Stanturf, this volume). Yet, because nearly all temperate and boreal forests have been influenced to varying and unknown degrees by aboriginal man, as well as being subject to continually changing climate and other natural disturbances, seeking to restore an ecosystem to a single assumed pre-human condition is neither a realistic nor relevant goal. Instead, managers must study the past disturbance history of the system, and develop a working cognitive model of the desired future condition for that ecosystem. Because a "desired condition" is, by definition, an artifact of society, the desire for restoration will often simply reflect a shift in societal land-use preferences. In other cases, restoration efforts will focus on forest ecosystems that have been altered or degraded by urbanization, agriculture, or silvicultural practices.

Various disturbances, both anthropogenic and unrelated to man, historically maintained a shifting mosaic of different successional stages, forest types, and structural conditions across forested landscapes. A variety of vegetative conditions made ecosystems and species resilient in the face of infrequent severe disturbances such as hurricanes or stand-replacing wildfires. But the increasing influence of humans on temperate and boreal forests has led to widespread changes in these systems. The primary impact of humans on some forests has come from intensive timber management, while other forests have been impacted by fire exclusion. In some systems, a variety of human-mediated forces have worked together. Many forest ecosystems today show reduced biodiversity, fewer structural components, less coarse woody debris, and different stand and landscape-level patterns than those that previously characterized them (Walker 1993; DeLong and Tanner 1996; White and Walker 1997; Linder and Östlund 1998; Siitonen 2001; Carroll et al. 2002). These current traits are believed to be related to lowered, overall resilience of forest systems (Franklin 1993; Franklin and Forman 1987; Hunter 1999).

Reliance on natural disturbances to restore forest ecosystems to their previous condition would not be feasible due to their stochastic nature, and would ignore the important role often played by man. Although silviculture was not historically used for restoration purposes, it can provide landowners and managers with the tools to culture forests for restoration. Indeed, silviculture has been described as a process of creating, maintaining, or restoring an appropriate balance of essential components, structures, and functions to ecosystems that ensure their long-term vitality, stability, and resiliency (Nyland 2002). Silviculture provides many of the tools to restore and maintain ecosystems, especially if they are used to approximate those disturbance agents that historically shaped the system. Restoration is a relatively new focus, but the time-tested responses of forest ecosystems to various silvicultural practices (prescribed burning, regeneration methods, herbicides, etc.) are already fairly predictable and well understood (Table 11.1). Once ecosystems have been restored to specific desired conditions, silvicultural practices can be used to maintain them.

In this chapter, we discuss the challenges inherent in determining restoration goals and fitting appropriate cultural practices to them. We then review the role of fire as a

*Table 11.1* Restoration Uses of Some Traditional Silvicultural Practices

| Silvicultural Practice | Restoration Uses |
|---|---|
| Prescribed burning | To achieve desired stand structures; to enhance plant community diversity; to improve wildlife habitat; to maintain fire-dependent communities; to restore function |
| Harvesting | To create environmental conditions necessary to regenerate even-aged or uneven-aged stands; to achieve desired stand and landscape structure; to provide income for landowner |
| Intermediate cuttings | To tend established stands; to provide desired stand density, composition, and structure; to reduce fuel loading; to provide income |
| Planting and seeding | To reestablish desired species on areas where they cannot be regenerated naturally |
| Herbicide application | To control or remove exotic species; to alter or maintain desired stand structure and composition |

disturbance agent and the effects of nearly a century of fire exclusion on temperate and boreal ecosystems. We consider a number of different case studies in the restoration of temperate and boreal forests, with a special emphasis on the use of fire.

## 11.2 *Determining restoration goals*

Ecosystem restoration can have many goals. It may involve reintroducing particular species to the forest; in northern Europe, native broadleaved species such as beech (*Fagus* spp.), birch (*Betula* spp.), and oaks (*Quercus* spp.) are being planted on sites previously converted to nonnative conifers (Madsen et al., this volume; Spiecker and Hansen, this volume). On public lands in the U.S., a common objective is the restoration of old-forest conditions, a concept popular in the public mind, although often poorly defined (O'Hara and Baker, this volume). Restoration goals on private lands may be entirely different. Because most private landowners must generate income from their lands to pay taxes and other management costs, timber harvest may be a component of any restoration activity. Some landowners may factor in additional values of restored ecosystems (aesthetics, conservation, wildlife, biodiversity, etc.) to balance the benefits and costs of the restored ecosystem (Mitchell et al. 2000). Whatever the goal, a basic tenet is that restoration, to be successful in the long term, must benefit local people in some manner (Landers et al. 1995).

Aesthetics should be considered in the development of restoration goals. Although often not explicitly stated, the physical appearance of the forest is a critical aspect of the perception of a desired future condition, especially on public lands (Gobster 1996). Treatments that result in aesthetically attractive forest stands are likely to garner public acceptance, while manipulations producing results perceived as unattractive may be controversial. Managers should consider aesthetics when planning, and work to educate the public on the ecological value of intermediate forest conditions that may be perceived as aesthetically unattractive.

A basic requirement of any restoration plan is a clear definition of a desired future condition. Yet such objectives are moving targets. Ecosystems continue to evolve in response to changing climates, disturbance patterns, and landuses, and the desires of landowners and society will continue to shift as well. Information is often lacking on the range of variation, dynamics, and characteristics of the ecosystem being restored (Noss 1985; White and Walker 1997), making it impossible to know the exact condition of an ecosystem at a prior time, or the precise sequence of disturbances that shaped it. Because the degree to which any mix of cultural practices simulates the historical disturbance regime of a particular ecosystem is a matter of interpretation, restoration efforts are as much art as science.

Managers face the further challenge of recreating an ecosystem that probably varied widely over temporal and spatial scales. Issues such as fragmentation and the invasion of exotic species require landscape-level and even regional perspectives (Galley and Wilson 2001). Because of all these factors, restoration must be a long-term effort and goals are likely to be general rather than specific. Silviculture can provide the tools to create and sustain the desired future condition. However, successful ecosystem restoration efforts will require both perseverance and a flexible, adaptive management approach that combines knowledge and skills from both the biological and social sciences (Figure 11.1).

## 11.3 *Fitting cultural practices to restoration goals*

Resource managers and landowners who attempt to restore and maintain ecosystems must educate themselves about the nature of the disturbance regimes, both anthropogenic and natural, that historically shaped the system. Once managers have developed a cognitive model of a desired future condition, they can develop a plan to restore those conditions to the landscape. Silvicultural practices provide the appropriate tools.

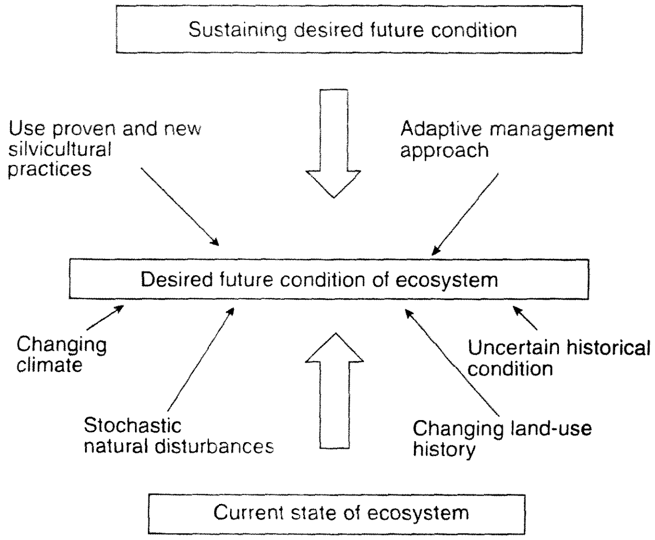



*Figure 11.1* Factors that influence the desired future condition of ecosystems and the management approach to sustain that desired condition.

Cultural practices can mimic many features of natural disturbances. For example, clearcuts open a portion of a forest to greater solar radiation, much as a windstorm might, and soil moisture can increase soon after harvest, just as it would after many types of natural stand-replacing disturbance. Soil nutrients are more available after anthropogenic or natural disturbances, and early-successional species often invade a clearcut just as they might after a windstorm that blows down a portion of a forest. But silvicultural practices may differ from natural disturbance in ways that may affect the condition of the forest such that the goals of the landowner are compromised. The chief difference is that harvesting removes woody biomass while a natural disturbance does not. In natural disturbances, the dead trees remain in the system and are important to wildlife and as sources of coarse woody debris (Jonsson and Kruys 2001). Managers can mitigate the effects of woody biomass removal by designing harvest strategies that leave tops of cut trees on site, or that retain some of the overstory standing as either dead or live trees.

Similarly, group-selection harvesting can approximate small openings in a forest that might have resulted from a lightning strike or a small group of trees killed by insects or disease. Thinning can imitate the natural mortality that occurs as stands age, or the selective mortality that occurs in windstorms, disease or insect outbreaks, etc. Again, these harvesting disturbances differ from natural disturbance by the removal of trees. The significance of this biomass removal to the desired future condition of the stand, and whether the impact can be lessened through the use of partial overstory retention or other means, will depend on the ecosystem in question.

Access is another way that silvicultural practices differ from natural disturbances in their impact on ecosystems. Road access is necessary to carry out most stand-based treatments, to transport people and equipment to the stand or to remove merchantable fiber, or both. Because establishing a new road on a landscape is the equivalent of adding a new ecosystem to an existing one (Lugo and Gucinski 2000), road networks have the potential to greatly impact forest landscapes (Trombulak and Frissell 2000). Building, operating, and maintaining roads constitute new forms of disturbance; the earth movement during road building can disturb whole watersheds. Roads fragment the landscape and can allow access by invasive species. Yet roads can also help landowners respond to wildfire, manage insects or disease, and realize a profit on their forested land. The effects of roads may be thus viewed as positive as well as negative, depending on the ecosystem component in question (Trombulak and Frissell 2000; Lugo and Gucinski 2000). Opportunities to mitigate the adverse impacts of roads include careful choice of site, careful construction practices, use of temporary or seasonal roads, and abandonment and restoration of old roadbeds.

Fire has long been used to accomplish land management objectives (Hämet-Ahti 1983; Wade and Lunsford 1989; Pyne et al. 1996). Historically, fire acted as an ecological process on varying gradients of soil, topography, hydrology, and climate to shape vegetative patterns and character. Prescribed fire can be used to complement other agents of disturbance, both anthropogenic and natural, and to maintain a shifting mosaic of different seral stages of the restored ecosystem over the landscape. If properly used, prescribed fire can restore structure, composition, and function of certain ecosystems to more closely resemble desired conditions.

In many situations, however, the use of fire is not feasible. Fire carries with it risks to human habitation, concerns about liability, difficulties in obtaining burning permits, effects of smoke, limited burning days, and the costs of applying, controlling, and monitoring burns (Wigley et al. 2002). In some circumstances, selective herbicides can provide the disturbance functions of fire. Selective herbicides allow managers to manipulate species composition in the understory, control stand structure, and selectively remove undesirable exotic plants (Grilz and Romo 1995; Wigley et al. 2002). At the same time, herbicides do not have the same ecological impact of fire; they cannot scarify leguminous seeds to enhance germination or open serotinous cones. In some parts of the boreal zone, such as Scandinavia, the use of herbicides in forest management is prohibited.

Neither prescribed fire nor herbicide application can address every restoration objective; sometimes a combination of the two practices may be called for. Because public support is critical, efforts to educate the public about the environmental effects of both prescribed fire and herbicides, and the reasons for their use, may pay large dividends. In any case, managers must exercise considerable judgment when deciding to use either fire or herbicides or both for restoration purposes.

Most decisions regarding desired future conditions require a landscape-level approach (Boyce 1995). Although cultural treatments are applied to stands, a landscape-level perspective is needed for such issues as connectivity, fragmentation, wildlife habitats, sustained yield, and endangered and threatened species. At a minimum, treatments applied at the level of the stand should complement landscape-level objectives.

## *11.4 Fire as a disturbance agent in temperate and boreal forests*

Historically, fire was the dominant disturbance that shaped the character of many temperate and boreal ecosystems (Pyne et al. 1996; Bonnicksen 2000; Brown and Smith 2000). It often complemented other types of disturbances, such as hurricanes, tornadoes, ice storms, insect infestations, disease outbreaks and, more recently, harvests, because these events created conditions that predisposed disturbed areas to burn (Myers and Van Lear 1997; Brown and Smith 2000).

Fire regimes vary widely among and within geographic regions, making it difficult to generalize about regional responses to fire (DeLong 1998; Bergeron et al. 2002). The historical fire cycle of many ecosystems is subject to continuing scientific study and debate. For example, how did the fire cycle change in response to the arrival of the first aboriginal humans in the system? How did it change with the arrival of European settlers? How did a changing climate affect it?

Despite these challenges, fire scientists have devised systems for characterizing fire regimes, using variables such as intensity, severity, frequency, and extent (Agee 1993; Brown and Smith 2000). In parts of North America, for example, in moist to wet systems in northern hardwood forests, fires were so rare as to be effectively absent from the system (Table 11.2). Other ecosystems were subject to very frequent fires that burned with low intensity (understory fire regime). Typically, such understory fires were less severe, had short flame lengths, and had relatively little direct effect on the soil and overstory vegetation. Other areas burned infrequently, but with great intensity, and essentially all overstory trees were killed (stand-replacement fire regime). In other cases, fire caused selective mortality in the dominant vegetation or the effects of fire varied spatially and/or temporally between understory and stand-replacement regimes (mixed severity fire-regime).

In the temperate forests of North America, fire has been integral to the processes that maintained the structure, composition, and function of most ecosystems (Agee 1993; Duchesne 1994; Whelan 1995; Brown and Smith 2000). The pine and oak forests of the eastern U.S., the sequoia forests of the west coast, the conifer forests of the Rocky Mountains and the Sierra Nevada, as well as grassland ecosystems all depended on frequent fire. Boreal forests, on the other hand, are slower growing and less productive than most temperate forest systems, with slower accumulation of woody fuels that persist longer on the forest floor. While normal fire regimes in much of the boreal forest zone include infrequent, large, and often severe fires (Pyne et al. 1996; Viereck 1973), in other parts of the boreal zone, fire regimes are significantly different (Bergeron et al. 2001). There is a wider range of variation in what constitutes a natural boreal fire cycle than has previously been believed (Bergeron et al. 2002).

In unraveling fire histories, the role of anthropogenic burning must be considered. Aboriginal humans were often the dominant ignition sources, using fire to manage ecosystems for their benefit (Pyne et al. 1996; Bonnicksen 2000; Brown and Smith 2000). As early people learned to use and control fire, they complemented the natural lightning regime, increasing the frequency of fire and changing its seasonality (Bonnicksen 2000; Carroll et al. 2002). The frequent and often extensive anthropogenic and lightning-ignited fires, along with the herbivory that fire encouraged, created and maintained open woodlands, savannas, and prairies throughout much of the temperate forest zone in the U.S. When Columbus arrived, most of the eastern U.S. was a managed landscape composed of a mosaic of dense forests, woodlands, savannas, and prairies in various stages of succession, all created and maintained by burning. After populations of Native Americans plummeted in the 16th and 17th centuries, the level of burning declined and these open and dispersed ecosystems gradually became closed, contiguous forests (Williams 1989; McCleery 1993; Mann 2002; Pyne et al. 1996; Carroll et al. 2002).

## 11.5 Fire exclusion and the decline of fire-dependent ecosystems

Not until the early 1900s were there serious efforts to exclude fire as an ecological process in North America. A series of large wildfires in Wisconsin, Minnesota, and Idaho around the

*Table 11.2* Oak Restoration Options with the Shelterwood-Burn Method

| Option | Silvicultural Treatment |
|---|---|
| Regeneration of new oak-dominated stand | Harvest shelterwood following prescribed burn to release oak regeneration |
| Culture a two-aged stand with oak dominating both age classes | Retain shelterwood and withhold additional burns |
| Develop oak woodland or savanna | Retain shelterwood and resume burning at 2–4-year intervals |

From Brose et al. Using Shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites, *For. Ecol. Manag.*, 113. 125, 1998.

turn of the last century aroused public attention and concern. Cutover forests in the southeastern Coastal Plain were burning so frequently — often annually — that forest regeneration was impossible. Slash fires following logging in the Appalachian Mountains burned severely, causing devastating off-site effects, such as erosion, sedimentation, and air pollution from smoke. In the early decades of the 20th century, the public, led by the Forest Service and state forestry commissions, began to see fire as an enemy to be suppressed at all costs (Pyne et al. 1996; Johnson and Hale 2002). These actions resulted in a widespread policy of fire exclusion.

Fire exclusion in fire-dependent ecosystems can be considered a form of disturbance, that is, a state of disorder, which changes the very nature of that ecosystem. Exclusion of fire had many unexpected and undesirable consequences (Covington and Moore 1994; Brennan et al. 1998; Landers et al. 1995; Brose et al. 2001). In fact, the ecosystem restoration movement in the U.S. can be linked closely to the threatened or declining status of fire-dependent ecosystems and the species within them, such as longleaf pine in the southeast (Brockway et al., this volume) and ponderosa pine in the southwest (Kaufmann et al. this volume).

In Europe, a similar situation has evolved, but with earlier origins. The agricultural and forest practices of the British and French empires became the standard by which to measure forest ecosystem health (Pyne et al. 1996). Intensive agriculture supplanted fire and heavy grazing by domestic animals reduced fuel accumulation. A century of intensive forestry removed the threat of wildfire and prescribed burning was prohibited.

The situation is quite different in the boreal forest of Canada and Alaska. In some areas that have yet to be accessed by roads, the major human impact has been fire suppression. Other vast tracts receive no suppression effort at all and still experience the large wildfires that are part of the natural fire regime. For example, between 1976 and 1991, northwestern Ontario had at least one wildfire of greater than 100 $km^2$ per year (Racey et al. 1991), while in Alaska, at least one wildfire of more than 400 $km^2$ occurs in a typical year. While fire suppression efforts in parts of Canada and Alaska began only at the start of the 20th century, in other areas suppression was not instituted until the 1970s. Because of the vast areas involved, lack of access, and limited budgets, the effectiveness of organized suppression activities is debated. There are indications that, at least in western Canada, the number of acres burned increased in the second half of the 20th century (Kurz and Apps 1999; Van Wagner 1988). Indeed, Bergeron et al. (2002) make the point that for vast areas of Canada, maintaining existing biodiversity is a more appropriate management goal than seeking to restore it.

It is apparent that fire has been an important factor shaping many forest ecosystems around the world. Attempts to exclude it have resulted in many undesirable consequences. While it is unlikely that fire will ever return to its historical importance, certain fire-dependent ecosystems can be managed with fire to restore and maintain their historical character. Where it is not possible to use fire in a management context, other silvicultural tools may be appropriate to create and maintain forests similar to those created and maintained by fire.

## *11.6 Cultural practices for restoring and maintaining ecosystem function in temperate forests*

### *11.6.1 Maintaining oaks on productive sites in the eastern U.S.*

Fire played a major role historically in maintaining oak (*Quercus*)-dominated forests on productive sites in the eastern U.S. As a result of fire exclusion, oak forests on good sites are now declining. Because oaks are typically unable to regenerate in dense shade, they have been replaced by shade-tolerant species where small canopy-gap disturbance regimes dominate. When large canopy openings occur, such as after clearcut regeneration harvests, oaks are unable to compete with the fast-growing mesophytic species that colonize recently harvested sites (Abrams 1992; Loftis and McGee 1993; Lorimer 1993; Brose and Van Lear 1998). For decades, silviculturists puzzled over the problem of securing vigorous oak regeneration on good-quality sites in the eastern U.S. Prescribed burning in hardwood stands was not considered feasible because of the widely recognized damage to boles of overstory trees from wildfires, and more recent accounts of bole damage from prescribed fires (Wendell and Smith 1986).

Recently, we have come to understand better the role of fire in these forests. Fire often swept through hardwood forests of the eastern U.S. in the past, shaping the character of forests and maintaining oak as a dominant component in the landscape (Abrams 1992; Brose et al. 2001; Carroll et al. 2002). Recent studies have shown that understory burning in mature mixed-hardwood stands at 2- to 4-year intervals enhanced oak advance regeneration in the Piedmont region of South Carolina (Barnes and Van Lear 1998). These low-intensity burns produce little damage to boles of larger crop trees and reduce understory and midstory density, allowing more sunlight to reach the forest floor. However, a disadvantage of this technique is that multiple burns are required to reduce competition and increase the abundance and size of oak regeneration sufficiently to where harvest cuts would result in successful oak regeneration.

Brose and Van Lear (1998) and Brose et al. (1998) developed a more efficient and financially attractive technique using fire to regenerate oaks — a shelterwood-burn method that has produced excellent results in the Virginia Piedmont (Figure 11.2). The prescription calls for an initial shelterwood cut in oak-dominated hardwood stands followed in several years by a moderate to high-intensity fire (flame lengths of about 1 m) through the advance regeneration. This technique has successfully converted advance regeneration under mature mixed-hardwood shelterwood stands from yellow poplar (*Liriodendron tulipifera*) domination to predominately oak regeneration. In addition, the oak regeneration is of good form, competitively sized, and sufficiently free to grow so that it should be capable of forming a new oak-dominated stand when the overstory is removed (Brose et al. 1998).

A key ingredient of the prescription is achieving fires of sufficient intensity to significantly set back competing species. The silvicultural prescription simulates, to a degree, the combined events of overstory disturbance caused by wind or ice storms followed by fire, related disturbances that have shaped the composition of oak ecosystems for millennia (Brose et al. 2001; Van Lear and Brose 2002). This method assumes that there is advance regeneration of oak, albeit noncompetitive, prior to the initial cut. If not, it will be necessary to begin understory burning and delay the initial shelterwood cut until adequate oak advance regeneration is in place.

There are several restoration options following the burn in this technique (Figure 11.2). If regeneration of an even-aged oak-dominated stand is the goal, the shelterwood can be removed to allow the regeneration to develop in full sunlight. If, for aesthetic and other reasons, a continuous cover of high forest is desired, the shelterwood can be retained to allow the oak-dominated regeneration and the shelterwood to develop into a two-aged stand. Both of these options will maintain oaks after harvest and reverse the decline of oak forests on good-quality sites. A third option is to continue burning at frequent intervals (2- to 4-year intervals) to encourage the development of oak woodlands, or savannas if continued long enough. These open, grass-dominated ecosystems are now rare in the eastern U.S., but were once common when frequent fires controlled vegetative patterns (Carroll et al. 2002).

### 11.6.2 *Maintaining Table Mountain/pitch pine ecosystems in the southern Appalachians*

Table Mountain pine (*Pinus pungens*)/pitch pine (*Pinus rigida*) stands became rarer in the southern Appalachian mountains during the past century (Clinton et al. 1993). As with

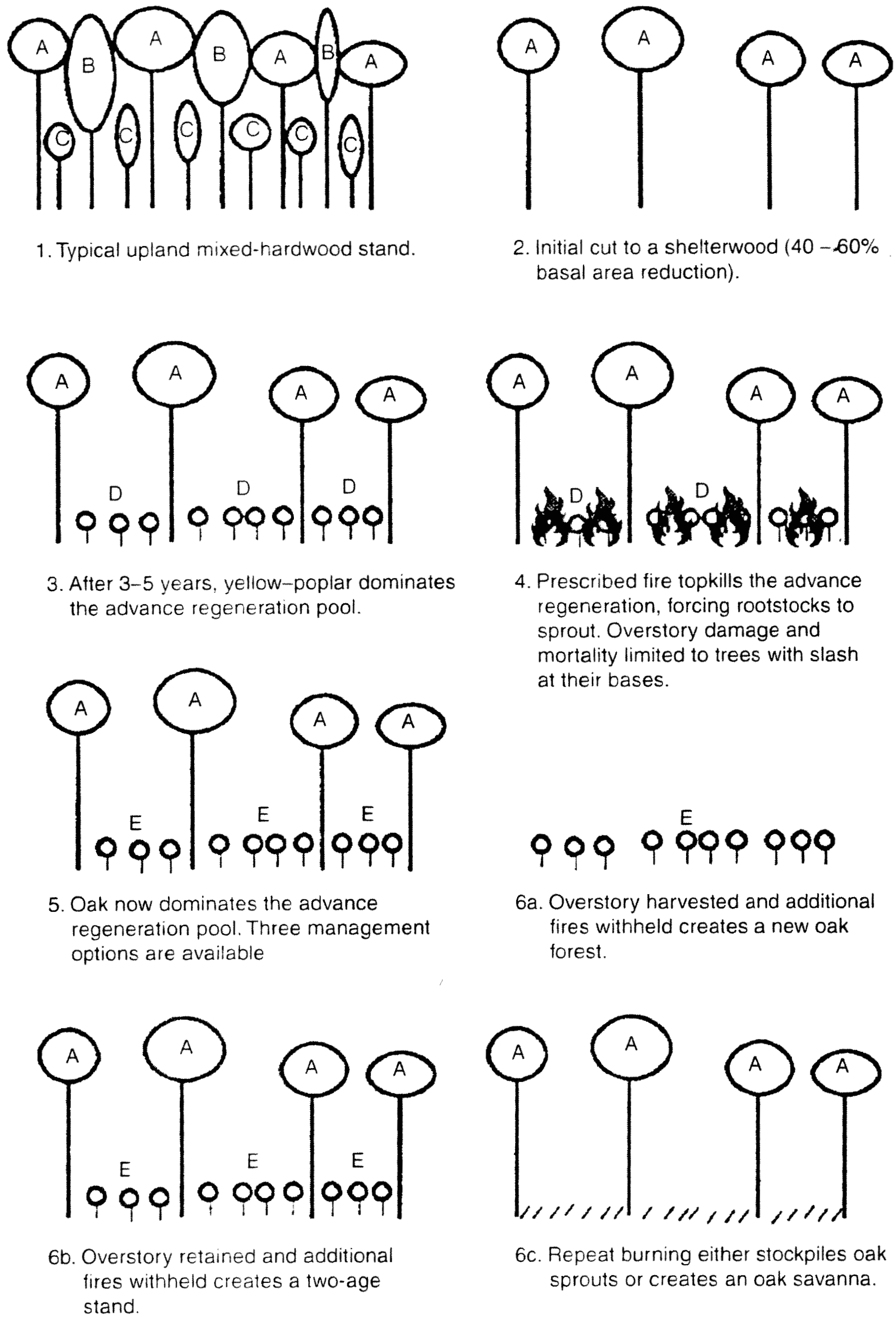
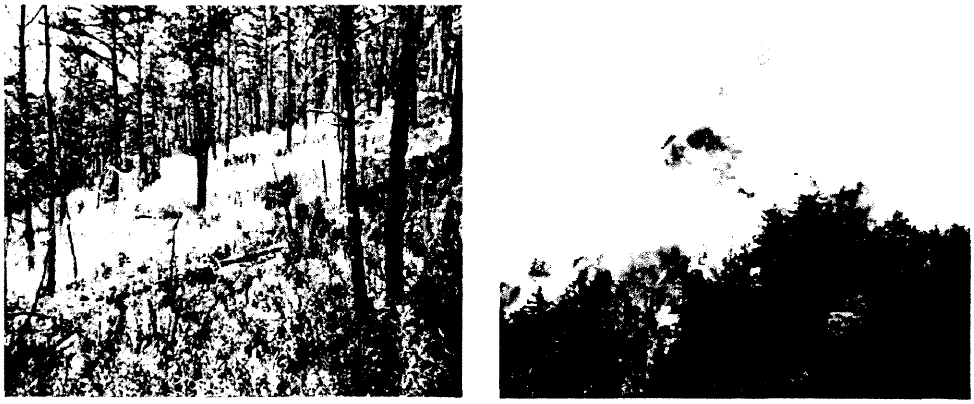



*Figure 11.2* Shelterwood-burn technique for regenerating oak stands on productive upland sires in the Piedmont. A = high-quality dominant oaks; B = hickories, poor-quality oaks, and yellow poplar; C = American beech, flowering dogwood, and red maple; D = mixed hardwood regeneration dominated by yellow poplar; E = mixed hardwood regeneration dominated by oak. (From Brose and Van Lear, Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands, *Can. J. For. Res.*, 28, 331, 1998.)



(A) (B)

*Figure 11.3* (A) Open woodland conditions in a Table Mountain/pitch pine stand following four surface burns over a 12-year period. (Photo by Russell Randles.) (B) Stand replacement prescribed burn for fuel reduction and regeneration in Table Mountain/pitch pine stands. (Photo courtesy of Joint Fire Science Program and Tom Waldrop.)

other fire-dominated pine ecosystems (Brockway et al., this volume; Kaufmann et al., this volume), the Table Mountain/pitch pine ecosystem is in decline because of fire exclusion. Isolated stands of Table Mountain pine and pitch pine (these two species often coexist) occur on exposed, generally southwest-facing slopes, and grow on xeric sites. Because of inaccessibility, small size, and low quality of trees in this type, it is considered unmerchantable. Maintaining it as a component of the larger southern Appalachian ecosystem is primarily a matter of conservation and land stewardship rather than economics, and is of concern mostly on public lands.

Ecologists and fire scientists debate the type of fire regime that historically maintained this pine ecosystem. In the absence of fire, low-quality hardwood species and mountain laurel (*Kalmia latifolia*) replace these pine stands (Elliott et al. 1998; Waldrop and Brose 1999). Cyclic southern pine bark beetle (*Dendroctonus frontalis*) epidemics accelerate the rate of succession to hardwoods.

Single high-intensity prescribed burns have limited success in restoring Table Mountain/pitch pine stands (Elliott et al. 1998; Waldrop and Brose 1999). Thick layers of accumulated duff must be reduced to obtain seedling regeneration of these species (Mohr et al. 2002). Periodic burning at 3- or 4-year intervals with moderate- to high-intensity fires creates and maintains the type in open woodland conditions (Figure 11.3A) (Randles et al. 2002). Historically, a mixed-severity fire regime with both surface fires and stand-replacement fires (Figure 11.3B) was probably typical in this type. This fire regime kills part of the overstory, reduces the importance of ericaceous shrubs such as mountain laurel, prepares a favorable seedbed, and favors herbaceous cover and pine regeneration.

## 11.7 Cultural practices for restoring and maintaining ecosystem function in boreal forests

The level of human impact in the circumpolar boreal zone and the associated need for forest restoration varies greatly. Much of the forestland of Fennoscandia has been managed intensively for centuries, via widespread slash-and-burn conversion of forests to farmland, followed by intensive silviculture and the exclusion of wildfire (Hämet-Ahti 1983; Östlund et al. 1997). At the other end of the spectrum lie Alaska and portions of boreal

Canada, where large areas of forest have never been harvested or even accessed by roads (Sanderson et al. 2002). For some of boreal North America, the primary human impact comes in the form of fire suppression. Fire has shaped the boreal biota over centuries and has directed the biological structure of the landscape (Rowe and Scotter 1973; Zackrisson 1977; Pyne et al. 1996). The fire-return interval is long relative to temperate zones; fires can be large, intense, and smolder for a long time. While there is variation across the region, the typical boreal forest wildfire is stand-replacing (Figure 11.4). Trees regenerate from seed from nearby unburned patches of forest (e.g., *Picea glauca*), from seed released from serotinous cones (e.g., *Pinus banksiana* and *Pinus contorta*), or by sprouts from surviving belowground parts (e.g., *Betula* spp. and *Populus tremuloides*).

Boreal silvicultural strategies are being widely redesigned with the goal of maintaining or restoring specific attributes of forest ecosystems at the same time that they yield usable fiber. Harvest prescriptions can be designed for a variety of different purposes, including approximating some aspects of wildfire (Bunnell 1995; Delong and Tanner 1996), promoting the development of old-forest characteristics (Coates and Burton 1997; Singer and Lorimer 1997; Bergeron and Harvey 1997; Burton et al. 1999), or increasing the diversity of the ecosystem (Haila 1994; Lieffers et al 1996; Lämås 1996). In both Canada and Alaska, timber is commonly harvested during the winter, when frozen ground can improve access to merchantable stands. Ice bridges and temporary winter roads can be

*Figure 11.4* Stand replacement fire in black spruce in Alaska. (Photo courtesy US Department of Agriculture, Forest Service.)

used to avoid some of the negative effects of permanent, all-season roads (Rhoads 1974; Blinn 1998).

### 11.7.1 *Restoring coarse woody debris and biodiversity to the managed forests of Sweden*

The boreal forests of Fennoscandia are adapted to centuries of anthropogenic- and lightning-caused fires (Zackrisson 1977; Kuusela 1992). Beginning early in the last century, however, intensive agriculture and plantation forestry gradually changed these forests (Östlund et al. 1997). The long history of intensive human use included slash-and-burn conversion to farm and grazing land, establishment of plantation forests of Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), and exploitative harvesting for charcoal and sawlogs (Hämet-Ahti 1983). The amount of coarse woody debris and the number of standing dead trees declined precipitously, and with this loss of fuel, wildfires became rare (Lämås 1996; Pyne et al. 1996). Wildfires that did occur were suppressed. By the 1980s, fire was virtually eliminated from the forests of Fennoscandia.

In Sweden, the combination of slash-and-burn agriculture, intensive forestry, conversion to conifer plantations from native broadleaved forests, and ultimately fire exclusion resulted in a dramatic loss of biodiversity (Esseen et al. 1997). Nearly 200 species of vascular plants, 55 species of bryophytes, 100 species of lichens, and 10 species of mammals were considered endangered or regionally extinct by the year 2000 (Gardenfors 2000), and many of these species are dependent on old, dying, or dead trees (Berg et al. 1994). In 1993, the maintenance of biodiversity was made equally important with timber production in Swedish forest policy (Lämås and Fries 1995). A new strategy was adopted to restore biodiversity, which is based on a system of forest reserves and management that mimics natural processes. However, because only 0.5% of productive forestland in Sweden is in reserves, most of the restoration effort is occurring in concert with fiber production (Fries et al. 1997; Hansen et al. 1991).

Attention to coarse woody debris is a fundamental part in this approach. Coarse woody debris provides habitat for plants, animals, and fungi and is important in nutrient cycles and carbon budgets (Harmon et al. 1986; Sturtevant et al. 1997). New forest management strategies are being advanced that allow some trees, or some patches of trees, to become very large and old, or that include provisions for generating snags. In addition to acting as a bank of coarse woody debris, large, old trees are a source of future small-scale disturbance. In northern Sweden, uprooting of large trees during natural windthrow has been shown to lead to greater habitat heterogeneity and a significant increase in bryophyte diversity (Jonsson and Esseen 1990).

Fries et al. (1997) and Angelstam (1998) describe the three major site types in boreal Sweden and suggest management options. Under natural conditions, two of these ecosystems, Scots pine sites and mesic sites with either deciduous species or Norway spruce, are fire disturbed, and are viewed as well adapted to large-scale disturbances. On Scots pine sites, harvest strategies would leave 5 to 20 seed trees standing per ha, and low-intensity prescribed burning would be conducted beneath seed trees. Efforts would be made to conserve or reestablish native broadleaved tree species, either through leaving birch and other deciduous species uncut, or by planting. Such postfire, successional forests are considered a biotope of high conservation value (Lämås and Fries 1995); the Swedish government provides financial incentives for landowners to use prescribed burning rather than mechanical site preparation.

For mesic-type sites, clear felling of conifers with retention of deciduous species is recommended (Fries et al. 1997). Rotations would be prolonged, with some stands allowed to develop to domination by aspen and birch. The third type of site, an uneven-aged Norway spruce forest, is viewed as highly sensitive to severe disturbance. The traditional management approach for such forests has been to clearcut and drain (or "ditch") them, followed by replanting with Norway spruce. Partial overstory retention, using either selection harvest systems or dense shelterwood harvesting systems, is now recommended on these sites (Fries et al. 1997), along with allowing at least a third of the shelterwood trees to remain on the site as a source of large snags.

Concerns about species conservation are forcing a reexamination of attitudes toward fire in Fennoscandia (Kuuluvainen et al. 2002). As more is learned about the ecological role of fire in European boreal forests, it is likely that the use of prescribed fire will increase. Nevertheless, the beneficial role of fire in the perpetuation of nature preserves and historically valued landscapes has yet to be widely accepted in Europe (Pyne et al. 1996).

### *11.7.2 Restoring components of natural disturbance to managed forest landscapes in Canada*

Although harvesting in the boreal forest of Canada began in the early 20th century, the vast majority has occurred since the 1970s, when rates of harvest accelerated substantially. Some of the interest in new silvicultural approaches in the boreal zone of Canada thus comes from a desire to maintain natural characteristics of newly-accessed land, rather than from a restoration need. In other situations, researchers are modifying the methods developed to maximize wood production and redesigning them to provide a wider variety of forest attributes.

The forest landscape that results from intensive forest management differs dramatically from forests generated by wildfire (DeLong and Tanner 1996; Bergeron et al. 2002). Wildfire creates a complex pattern of disturbance on the landscape, consisting of a mosaic of different-aged patches and irregular boundaries. Many patches exceed 500 ha in size, containing unburned areas within them in which trees sometimes grow very old (Eberhart and Woodward 1987). As it is currently practiced, intensive forest management results in a forest landscape composed of regularly dispersed clearcuts of less than 60 to 100 ha in size (DeLong and Tanner 1996). As this approach moves toward a fully regulated forest, trees older than the rotation age will gradually become underrepresented on the landscape until they disappear completely (Bergeron et al. 2002).

Different silvicultural approaches have been suggested to mimic natural disturbances. Increasing the size of some harvest units to greater than 500 ha would result in a landscape pattern of disturbance more similar to the pattern of wildfire (DeLong and Tanner 1996). Such occasional large harvest units could have economic advantages that would compensate for the costs of irregular unit boundaries and leaving patches of trees uncut. Because the vertebrate fauna of boreal and sub-boreal British Columbia are adapted to large-scale disturbance, the effects of clearcutting would more closely approximate those of wildfire if more woody debris, standing snags, and live trees were left (Bunnell 1995). Natural forest age structure could be maintained through the use of rotations of various lengths (Burton et al. 1999).

### *11.7.3 Mixed-wood management in Canada's southern boreal forest*

The northern mixed-wood forest occurs on mesic sites in a swath extending from Alaska to eastern Canada. It is composed primarily of white spruce, balsam fir (*Abies balsamea*), and trembling aspen, and lesser amounts of black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) (Greene et al. 2002). The mixed-wood ecological region includes about 250,000 km$^2$ of northern Alberta (Cumming et al. 1996). Most of the area has never been harvested, and remains inaccessible by road, although it is crisscrossed by seismic investigation lines and natural gas pipelines. Fire is the main natural disturbance agent, and fire suppression is likely the most significant impact of European settlers (Cumming et al. 1996). Trembling aspen is usually the first species to dominate following fire, while white spruce gradually colonizes and develops in the understory. If undisturbed, uneven-aged stands of white spruce and balsam fir become dominant.

The traditional silvicultural methods used to manage these stands have focused on establishing relatively pure stands of white spruce (Greene et al. 2002). Regenerating white spruce is difficult; however, the species grows slowly and is easily overtopped by broadleaved trees, shrubs, and grass. Even when pure spruce stands can be established successfully, however, they have lower biodiversity than mixed species stands (Burton et al. 1992). At the same time, stands in which the majority of the overstory is trembling aspen are typically not managed for conifer production at all (Lieffers et al. 1996).

In an effort to capture the potential spruce yield on such primarily deciduous sites, as well as improve the biodiversity value of sites that have been managed for white spruce, a variety of mixed-wood silvicultural options have been proposed (Lieffers et al. 1996; Man and Lieffers 1999). For sites where a spruce seed source is lacking, clearcutting aspen followed by underplanting of white spruce early in the development of the regenerating aspen stand has been proposed. Another option is using heavy mechanical site preparation to control the shrub understory of an open, low-vigor stand of aspen, followed by underplanting with white spruce 10 or more years before harvesting the trembling aspen overstory. Sites would need to be carefully chosen so as to allow for the removal of the aspen overstory without damaging the young white spruce (DeLong 2000). On sites where spruce occurs in the overstory, shelterwood and seed tree harvesting options are recommended as a means of retaining a spruce seed source on the site. Such ecologically based, mixed-wood management may sustain more ecosystem components than the current management system, and the public support it garners may result in greater security of tenure for industrial forestry on public lands (Lieffers et al. 1996).

### 11.7.4 *Landscape-scale burning in Alaska*

The boreal forests of Alaska have been harvested very little. Impacts of historical as well as recent timber harvesting are limited to the areas surrounding towns, along the limited State Forest road system, near major rivers where wood was cut for stern-wheeled riverboats, and around mining areas where wood was used for fuel (Wurtz and Gasbarro 1996). The total area disturbed in this way is a small fraction of Alaska's boreal zone. Fire suppression has had a larger impact than timber harvesting; however, the natural fire cycle remains the subject of some debate. Between 1898 and 1939, an estimated 1 million acres burned annually. With the founding of permanent settlements in the early 1900s, concerns about wildfire arose (Jewkes 1999). Due primarily to limited access, early suppression efforts were limited in scope and effectiveness.

Today, most of the land in Alaska is classified into one of four fire management categories. Inhabited areas are designated "Critical" because of the immediate threat of wildland fire to human life and shelter. Areas having desired resources such as accessible timber or late-seral wildlife habitat are classified as "Full," where initial attack is again practiced to reduce the spread of fire. Many areas remote from human occupation, constituting the majority of the state, are designated "Limited," and fires in these areas are monitored but not suppressed unless they threaten to spread to areas where fire protection is desired. Thus, most of Alaska still experiences a natural or seminatural fire regime. The fourth class, "Modified," is intended to provide a higher level of protection when fire danger is high and a lower level of protection when fire danger decreases, thus providing

*Figure 11.5* In interior Alaska, landscape-scale prescribed burns are conducted to enhance habitat for species such as moose. (Photo courtesy of Alaska Department of Fish and Game.)

increased flexibility in the selection of suppression strategies (Alaska Wildland Fire Coordinating Group 1998).

In interior Alaska, aggressive suppression in the immediate vicinity of settled areas has led to a disproportionate representation of conifers in older age classes. This pattern of succession in the absence of fire increases fire risk to nearby structures or communities and lowers the productivity of many wildlife species adapted to fire disturbance (Haggstrom and Kelleyhouse 1996). In such areas, managers are experimenting with stand-scale treatments such as willow crushing or aspen felling to maintain cover and browse on sites known to be productive for game species, such as moose (*Alces alces*) and grouse (*Bonasa* spp.). Stand-scale burning of aspen in spring, just before leaf-out, is also used on sites that are accessible by forest roads but away from communities.

In remote areas, large landscape-scale burns have been carried out using aerial ignition. These large burns are indistinguishable from natural fires and dramatically enhance habitat for a variety of wildlife species requiring early-seral vegetation, including moose, grouse, and a number of meso-carnivores (Figure 11.5).

## 11.8 Conclusions

Restoring ecosystems and maintaining them in a restored state is as much an art as a science. In most cases, managers are faced with the challenge of approximating some version of the ecosystem in question, with some uncertainty about the nature of this desired system. Managers can make use of a variety of tools to develop a cognitive model for the restored ecosystem, including fire histories, palynological reconstructions, comparative analysis of other systems, accounts of early explorers and settlers, and even old photographs. Once the desired future condition of the ecosystem has been determined, managers can use well-documented silvicultural practices to maintain the system in that general state. In keeping with the adaptive management approach, managers must continually reevaluate not only the target state of the ecosystem but also the methods used to maintain it there.

Long-established silvicultural practices can be used to culture restored ecosystems. Prescribed burning can simulate many of the effects of anthropogenic and lightning-ignited wildfire regimes and can be used to maintain historical stand structures and to direct composition and function of restored ecosystems. Harvesting systems can emulate, at least partially, those types of disturbances that created environmental conditions favoring reestablishment and maintenance of desired species and communities. Intermediate cuttings can control stand density and composition. Portions of the overstory can be retained as wildlife habitat, and as a source of future coarse woody debris. Herbicides can control exotic species and maintain desired stand structure. Species mixtures can be accepted and encouraged. Native species that have been lost from the system can be reintroduced. Seasonal roads can be used or permanent roads can be sited to minimize adverse roading impacts. Silviculture provides opportunities for landowners to realize a financial return from their forested land — an important consideration in the long-term maintenance of restored ecosystems.

Fire was the dominant factor that historically shaped the character of most temperate and boreal forests. However, a century-old policy of fire exclusion in North America and a longer one in Europe has erased the memory of fire's importance. Because the field of restoration ecology is rekindling the search for knowledge of the ecological processes that shaped ecosystems, interest in the ecology and use of fire will likely grow. Fire should be considered in the context of its role as an ecological process that shaped vegetative patterns in most ecosystems for thousands of years. Whether ignited by man or by lightning, fire has the potential to play an important role in forest restoration. Fire and other silvicultural practices can reestablish and maintain pattern and process in ecosystems around the world.

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## References

Abrams, M.D., Fire and the development of oak forests, *Bioscience*, 42, 346, 1992.

Agee, J.K., *Fire Ecology of the Pacific Northwest Forests*, Washington, DC, Island Press, 493, 1993.

Alaska Wildland Fire Coordinating Group, *Alaska Interagency Wildland Fire Management Plan*, 61 pp., 1998.

Angelstam, P.K., Maintaining and restoring biodiversity in European boreal forests by developing natural disturbance regimes, *J. Veg. Sci.*, 9, 593, 1998.

Barnes, T.A. and Van Lear, D.H., Prescribed fire effects on advanced regeneration in mixed hardwood stands, *South. J. Appl. For.*, 22, 138, 1998.

Berg, Å., Ehnström, B., Gustafsson, L., Hallingbäck, R., Jonsell, M., and Weslien, J., Threatened plant, animal, and fungus species in Swedish forests: distribution and habitat associations, *Conserv. Biol.*, 8, 718, 1994.

Bergeron, Y., and Harvey, B., Basing silviculture on natural ecosystem dynamics: an approach applied to the southern boreal mixed wood forest of Quebec, *For. Ecol. Manage.*, 92, 235, 1997.

Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P., and Lesieur, D., Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry, *Can. J. For. Res.*, 31, 384, 2001.

Bergeron, Y., Leduc, A., Harvey, B.D., and Gauthier, S., Natural fire regime: a guide for sustainable management of the Canadian Boreal Forest. *Silva Fenn.*, 36, 81, 2002.

Blinn, C., *Ice bridges. Forest Management Practices Fact Sheet: Crossing Options*, Series #4, University of Minnesota Extension Service, FS-7004-GO, 1998.

Bonnicksen, T.M., *America's Ancient Forests: From the Ice Age to the Age of Discovery*, John Wiley & Sons, Inc., New York, 594, 2000.

Boyce, S.G., *Landscape Forestry*, John Wiley & Sons, Inc., New York, NY, 239, 1995.

Brennan, A., Engstrom, R.T., Palmer, W.E., Herman, S.M., Hurst, G.A., Burger, L.W., and Hardy, C.L., Whither wildlife without fire, in *Transactions of the 63rd North American Wildlife and Natural Resources Conference*, 1998.

Brose, P.T. and Van Lear, D.H., Responses of hardwood advance regeneration to seasonal prescribed fires in oak-dominated shelterwood stands, *Can. J. For. Res.*, 28, 331, 1998.

Brose, P.T., Van Lear, D.H., and Cooper, R., Using shelterwood harvests and prescribed fire to regenerate oak stands on productive upland sites, *For. Ecol. Manage.*, 113, 125, 1998.

Brose, P., Schuler, T., Van Lear, D., and Berst, J., Bringing fire back — the changing regimes of the Appalachian mixed-oak forests, *J. For.*, 99, 30, 2001.

Brown, J.K., and Smith, J.P., *Wildland Fire in Ecosystems: Effects of Fire on Flora*, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-42, 2000.

Bunnell, F.L., Forest-dwelling vertebrate faunas and natural fire regimes in British Columbia: patterns and implications for conservation, *Conserv. Biol.*, 9, 636, 1995.

Burton, P.J., Ballisky, A.C., Coward, L.P., Cumming, S.G., and Kneeshaw, D.D., The value of managing for biodiversity, *For. Chron.*, 68, 225, 1992.

Burton, P.J., Kneeshaw, D.D., and Coates, K.D., Managing forest harvesting to maintain old growth in boreal and sub-boreal forests, *For. Chron.*, 75, 623, 1999.

Carroll, W.D., Kapeluck, P.R., Harper, R.A., and Van Lear, D.H., Historical overview of the southern forest landscape and associated resources, in *Southern Forest Resource Assessment*, U.S. Department of Agriculture, Forest Service, Southern Research Station General Technical Report SRS-53, 583, 2002.

Clinton, B.D., Vose, J.M., and Swank, W.T., Site preparation burning to improve southern Appalachian pine-hardwood stands: vegetation composition and diversity of 13-year-old stands, *Can. J. For. Res.*, 23, 227, 1993.

Coates, K.D. and Burton, P.J., A gap-based approach for development of silvicultural systems to address ecosystem management objectives, *For. Ecol. Manage.*, 99, 337, 1997.

Covington, W.W. and Moore, M.M., Southwestern ponderosa forest structure: changes since Euro-American settlement, *J. For.*, 92, 39, 1994.

Cumming, S.G., Burton, P.J., and Klinkenberg, B., Boreal mixed-wood forests may have no "representative" areas: some implications for reserve design, *Ecography*, 19, 162, 1996.

DeLong, S.C., Natural disturbance rate and patch size distribution of forests in northern British Columbia: implications for forest management, *Northwest Science Special Issue*, 72, 35, 1998.

DeLong, S.C., *Planting White Spruce under Trembling Aspen: 7-Year Results of Seedling Condition and Performance*. Research Branch, Ministry of Forests, Working Paper 54/2000, Victoria, B.C., 2000.

DeLong, S.C. and Tanner, D., Managing the pattern of forest harvest: lessons from wildfire. *Biodivers. Conserv.*, 5, 1191, 1996.

Duchesne, L.C., Fire and diversity in Canadian ecosystems, in *Biodiversity, Temperate Ecosystems, and Global Change*, T.J.B. Boyle and C.E.B. Boyle, Eds., Springer-Verlag, Berlin, 247, 1994.

Eberhart, K.E. and P.M. Woodward, Distribution of residual vegetation associated with large fires in Alberta, *Can. J. For. Res.*, 17, 1207, 1987.

Elliott, K.J, Hendrick, R.L., Major, A.E., Vose, J.M. and Swank, W.T., Vegetation dynamics after a prescribed fire in the southern Appalachians, *For. Ecol. Manage.*, 114, 199, 1998.

Esseen, P.-A., Ehnström, B., Ericson, L., and Sjöberg, K., Boreal forests, *Ecol. Bull.*, 46, 16, 1997.

Franklin, J.F., Preserving biodiversity: species, ecosystems or landscapes, *Ecol. Appl.*, 3, 202, 1993.

Franklin, J.F. and Forman, R.T.T., Creating landscape patterns by forest cutting: ecological consequences and principles, *Landscape Ecol.*, 1, 5, 1987.

Fries, C., Johansson, O., Pettersson, B., and Simonsson, P., Silvicultural models to maintain and restore natural stand structures in Swedish boreal forests, *For. Ecol. Manage.*, 94, 89, 1997.

Galley, E.M. and Wilson, T.P., Eds., *Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species, Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management*, Miscellaneous Publication No. 11, Tall Timbers Research Station, Tallahassee, FL, 2001.

Gärdenfors, U., Ed., Rödlistade arter I Sverige — The red list of Swedish species, Art Databanken, SLU, Uppsala, 393, 2000.

Gobster, P.H., Forest aesthetics, biodiversity, and the perceived appropriateness of ecosystem management practices, in *Defining Social Acceptability in Ecosystem Management: A Workshop Proceedings*, M.W. Brunson, L.E. Kruger, C.B. Tyler, and S.A. Schroeder, Eds., U.S. Department of Agriculture Forest Service, Pacific Northwest Station, General Technical Report PNW-369, 77, 1996.

Grilz, P.L. and Romo, J.T., Management considerations for controlling smooth brome in fescue prairie, *Nat. Areas J.*, 15, 148, 1995.

Greene, D.F., Kneeshaw, D.D., Messier, C., Lieffers, V., Cormier, D., Doucet, R., Coates, K.D., Groot, A., Grover, G., and Calogeropoulos, C., A biological and economic analysis of silvicultural alternatives to the conventional clearcut/plantation prescription in Boreal Mixed-wood Stands (aspen/white spruce/balsam fir), *For. Chron.*, 78, 281, 2002.

Haggstrom, D.A. and Kelleyhouse, D.G., Siliviculture and wildlife relationships in the boreal forest of Interior Alaska, *For. Chron.*, 72, 59, 1996.

Haila, Y., Preserving ecological diversity in boreal forests: ecological background, research, and management. *Ann. Zool. Fenn.*, 31, 203, 1994.

Hansen, A.J., Spies, T.A., Swanson, F.J., and Ohmann, J.L., Conserving biodiversity in managed forests, *Bioscience*, 41, 382, 1991.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Lattin, J.D., Anderson, N.H., Gregory, S.V., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack Jr. K., and Cummins, K.W., Ecology of coarse woody debris in temperate ecosystems, *Adv. Ecol. Res.*, 15, 133, 1986.

Hunter, M.L. Jr., Ed., *Maintaining biodiversity in forest ecosystems*, Cambridge University Press, Cambridge, U.K., 698 pp., 1999.

Hämet-Ahti, L., Human impact on closed boreal forest (taiga), in *Man's Impact on Vegetation*, W. Holzner, M.J.A. Werger, and I. Ikusima, Eds., Dr. W. Junk Publishers, The Hague, 201, 1983.

Jewkes, H.A., *History of fire control in Alaska*, University of Alaska Fairbanks, Fairbanks, AK, 153, 1999.

Johnson, A.S. and Hale, P.E., The historical foundations of prescribed burning for wildlife: a Southeastern perspective, in *The Role of Fire in Nongame Wildlife Management and Community Restoration: Traditional Uses and New Directions, Proceedings of a Special Workshop*, W.M. Ford, K.R. Russell, and C.E. Moorman, Eds., Nashville, TN, U.S. Department of Agriculture, Forest Service, Northeastern Station, General Technical Report NE-288, 11, 2002.

Jonsson, B.G. and Esseen, P., Treefall disturbance maintains high bryophyte diversity in a boreal spruce forest, *J. Ecol.*, 78, 924, 1990.

Jonsson, B.G. and Kruys, N., Eds., Ecology of woody debris in boreal forests, *Ecol. Bull.*, 49, 283, 2001.

Kurz, W.A. and Apps, M.J., A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector, *Ecol. Appl.*, 9, 526, 1999.

Kuuluvainen, T., Aapala, K., Ahlroth, P., Kuusinen, M., Lindholm, T., Sallantaus, T., Siitonen J., and Tukia, H., Principles of ecological restoration of boreal forested ecosystems: Finland as an example, *Silva Fenn.*, 36, 409, 2002.

Kuusela, K., Boreal forestry in Finland: a fire ecology without fire, *Unasylva*, 43, 22, 1992.

Landers, J.L., Van Lear, D.H., and Boyer, W.D., The longleaf pine forests of the Southeast: Requiem or renaissance, *J. For.*, 93, 39, 1995.

Lieffers, V.J., Macmillan, R.B., MacPherson, D., Branter, K., and Stewart, J.D., Semi-natural and intensive silvicultural systems for the boreal mixedwood forest, *For. Chron.*, 72, 286, 1996.

Linder, P. and Östlund, L., Structural changes in three mid-boreal Swedish forest landscapes, 1885–1996, *Biol. Conserv.*, 85, 9, 1998.

Loftis, D. and McGee, C.E., Eds., *Oak Regeneration: Serious Problems, Practical Recommendations. Symposium Proceedings*, 8–10 Sept. 1992, Knoxville, TN, U.S. Department of Agriculture, Forest Service, Southeastern Research Station, General Technical Report SE-84, Asheville, NC, 319, 1993.

Lorimer, C.G., Causes of the oak regeneration problem, in *Oak Regeneration: Serious Problems, Practical Recommendations*, D.L. Loftis and C.E. McGee, Eds., 8–10 Sept. 1992, Knoxville, TN, U.S. Department of Agriculture, Forest Service, Southeastern Station, General Technical Report SE-84, Asheville, NC, 14, 1993.

Lugo, A.E. and Gucinski, H., Function, effects, and management of forest roads, *For. Ecol. Manage.*, 133, 249, 2000.

Lämås, T., *Forest management planning for biodiversity and timber production*, Swedish University of Agricultural Sciences, Umeå; Report 3, 56, 1996.

Lämås, T. and Fries, C., Emergence of a biodiversity concept in Swedish forest policy, *Water Air Soil Pollut.*, 82, 57, 1995.

Man, R. and V.J. Lieffers, Effects of shelterwood and site preparation on climate and establishment of white spruce seedlings in a boreal mixedwood forest, *For. Chron.* 75, 837, 1999.

Mann, C.C., *The Atlantic Monthly*, 1491, March 2002.

McCleery, D.W., *American Forests — A History of Resiliency and Recovery*, revised edition, U.S. Department of Agriculture, Forest Service, and the Forest History Society, Durham, NC, 58, 1993.

Mitchell, R.J., Neel, W.L., Hiers, J.K., Cole, F.T., and Atkinson Jr., J.B., A model management plan for conservation easements in longleaf pine-dominated landscapes, Joseph W. Jones Ecological Research Center, Newton, GA, 24, 2000.

Mohr, H.H., Waldrop, T.A., and Shelburne, V.B., Optimal seedbed requirements for regenerating Table Mountain pine, in *Proceedings, Eleventh Biennial Southern Silvicultural Research Conference*, 20–22 Mar. 2001, Knoxville, TN, U.S. Department of Agriculture, Forest Service, Southern Research Station, General Technical Report SRS-48, 306, 2002.

Myers, R.K. and Van Lear, D.H., Hurricane–fire interactions in coastal forests of the south: a review and hypothesis, *For. Ecol. Manage.*, 103, 265, 1997.

Nyland, R.D., *Silviculture: Concepts and Applications*, 2nd ed. McGraw Hill, New York, NY, 682, 2002.

Noss, R.F., On characterizing presettlement vegetation: how and why, *Nat. Areas J.*, 5, 5, 1985.

Östlund, L., Zackrisson, O., and Axelsson, A.-L., The history and transformation of a Scandinavian boreal forest landscape since the 19th century, *Can. J. For. Res.*, 27, 1198, 1997.

Pyne, S.J., Andrews, P.L., and Laven, R.D., *Introduction to Wildland Fire*, 2nd ed., John Wiley & Sons, Inc., New York, NY, 769, 1996.

Racey, G.D., Abraham, K., Darby, W.R., Timmerman, H.R. and Day, Q., Can woodland caribou and the forest industry coexist: the Ontario scene, *Rangifer*, 7, 108, 1991.

Randles, R., Van Lear, D., Waldrop, T., and Simon, D., Periodic burning in Table Mountain-pitch pine stands, in *Proceedings, Eleventh Biennial Southern Silvicultural Research Conference*, 20–22 Mar. 2001, Knoxville, TN, U.S. Department of Agriculture, Forest Service, Southern Research Station, General Technical Report SRS-48, 114, 2002.

Rhoads, E.M., Ice crossings, *North. Eng.*, 5, 19, 1974.

Rowe, J.S. and Scotter, G.W., Fire in the boreal forest, *Q. Res.*, 3, 444, 1973.

Sanderson, E.W., Jaiteh, M., Levy, M.A., Redford, K.H., Wannebo, A.V., and Woolmer, G., The human footprint and the last of the wild, *Bioscience*, 52, 891, 2002.

Siitonen, J., Forest management, coarse woody debris, and saproxylic organisms: Fennoscandian boreal forests as an example, *Ecol. Bull.*, 49, 11, 2001.

Singer, M.T. and Lorimer, C.G., Crown release as a potential old-growth restoration approach in northern hardwoods, *Can. J. For. Res.*, 27, 1222, 1997.

Sturtevant, B.R., Bissonette, J.A., Long, J.N., and Roberts, D.W., Coarse woody debris as function of age, stand structure, and disturbance in boreal Newfoundland, *Ecol. Appl.*, 7, 702, 1997.

Trombulak, C.T. and Frissell, C.A., Review of ecological effects of roads on terrestrial and aquatic communities, *Conserv. Biol.*, 14, 18, 2000.

Van Lear, D.H. and Brose, P.H., Fire and oak management, in *Oak Forest Ecosystems — Ecology and Management for Wildlife*, The Johns Hopkins University Press, Baltimore, MD, 269, 2002.

Van Wagner, C.E., The historical pattern of annual burned area in Canada, *For. Chron.*, 64, 182, 1988.

Viereck, L.A., Wildfire in the taiga of Alaska, *Q. Res.*, 3, 465, 1973.

Wade, D.D. and Lunsford, J.D., *A Guide for Prescribed Fire in Southern Forests*, U.S. Department of Agriculture, Forest Service, Region 8, Technical Publication R8-TP 11, 1989.

Walker, J., Rare vascular plant taxa associated with the longleaf pine ecosystems: patterns in taxonomy and ecology, in *Proceedings, 18th Tall Timbers Fire Ecology Conference*, 30 May–2 June 1991, Tallahassee, FL, Tall Timbers Research Station, 105, 1993.

Waldrop, T.E. and Brose, P.H., A comparison of fire intensity levels for stand replacement of Table Mountain pine (*Pinus pungens* Lamb.), *For. Ecol. Manage.*, 1999.

Wendell, G.W. and Smith, H.C., *Effects of Prescribed Fire in a Central Applachian Oak-Hickory Stand*, U.S. Department of Agriculture, Forest Service, NE-RP-594, 8, 1986.

Whelen, R.J., *The ecology of fire*, Cambridge University Press, Cambridge, U.K., 1995.

White, P.S. and Walker, J.L., Approximating nature's variation: selecting and using reference information in restoration ecology, *Restor. Ecol.*, 5, 338, 1997.

Wigley, T.B., Miller, K.V., de Calesta, D.S., and Thomas, M.W., Herbicides as an alternative to prescribed burning for achieving wildlife management objectives, in *The Role of Fire in Nongame Wildlife Management and Community Restoration: Traditional Uses and New Directions, Proceedings of a Special Workshop*, W.M. Ford, K.R. Russell, and C.E. Moorman, Eds., Nashville, TN, U.S. Department of Agriculture, Forest Service, Northeastern Station, General Technical Report NE-288, 124, 2002.

Williams, M., *Americans and their Forests — A Historical Geography*, Cambridge University Press, New York, NY, 1989.

Wurtz, T.L. and Gasbarro, A.F., A brief history of wood use and forest management in Alaska, *For. Chron.*, 72, 47, 1996.

Zackrisson, O., Influence of forest fires on the North Swedish boreal forest, *Oikos*, 29, 22, 1977.