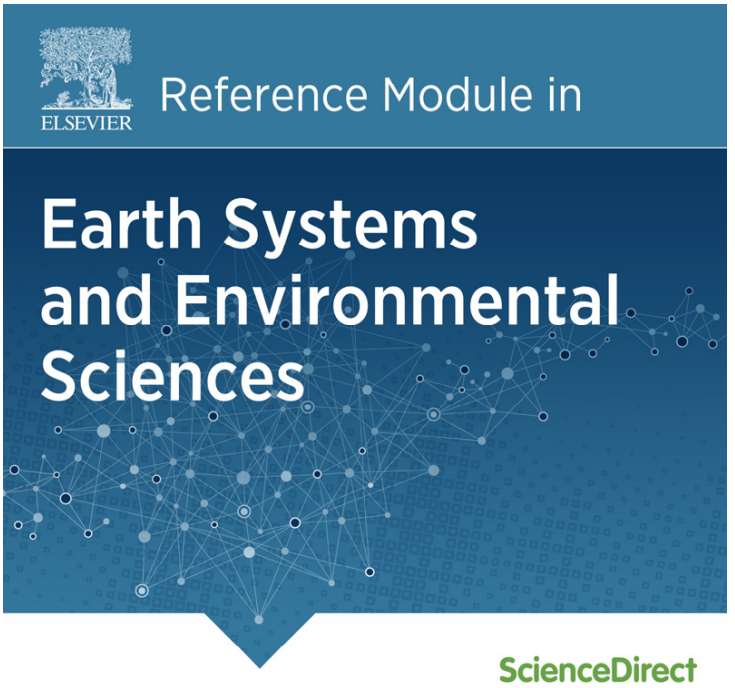

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Sustainable Forestry: Ecology and Silviculture for Resilient Forests

JR Boyle, JC Tappeiner II, and RH Waring, Oregon State University, Corvallis, OR, USA
C Tattersall Smith, University of Toronto, Toronto, ON, Canada

Abbreviations

ATFS American Tree Farm System (https://www.treefarmsystem.org/).
CSA Canadian Standards Association. Sustainable Forest Management Standard (http://www.csasfmforests.ca/)
FSC Forest Stewardship Council (https://us.fsc.org/en)
PEFC Programme for the Endorsement of Forest Certification (http://www.pefc.org/)
SFI Sustainable Forestry Initiative (www.sfiprogram.org)

Introduction

Sustainable forestry, or sustainable forest management (SFM), is the practice of managing forests to meet the current needs and desires of society for forest resources, ie, products, services, and values, without compromising the availability of these for future generations sensu Bruntdland et al. (World Commission on Environment and Development (1987)).

The concept of forest sustainability was developed in central Europe in the seventeenth to ninetieth centuries where there was a lack of wood, because of wars, need for fuel, clearing land for agriculture, and cover for game; all placed heavy demands on forests. It was important to produce high yields of forest products from the limited areas available for growing timber for human use (Bavarian State Ministry for Food, Agriculture and Forests, 2000). Stands were harvested when it was assumed that the mature stand yield was high and likely to decline. Forest sustainability came to mean controlling stand species composition, stocking, and growth so that a long-term nondeclining yield could be maintained indefinitely. Related issues generated the origin of the sustained yield concept that dominated forest management and policy in the National Forest system of the United States for many years (Floyd, 2002; Helms, 1998).

More recently, the concept of forest sustainability has grown to be inclusive of many complex dimensions (e.g. UNEP (2011)); and, especially on public forest lands, the sustained production of high yields of wood versus other forest values appears to be of less importance to many, especially urban people in highly developed countries, than it was in the middle of the twentieth century and earlier. New understanding of forests as ecosystems, along with societies' changing views of values derived from forests, has caused forest managers to adopt more comprehensive approaches to sustaining forests; concepts that in fact apply to values to be achieved outside of specific forest management units as we consider resource-dependent communities and biodiversity at landscape scales and migratory bird flight pathways and the climate change impacts of forest management. On many ownerships, water yield, habitat for wildlife, connectivity of habitats, scenery, recreation, and other values have greater societal interest than commercial wood production. Additionally, forests may be managed below the optimal stocking for wood production in order to reduce the potential for severe fire and/or insect damage. It is often difficult to agree on, quantify and set standards for values, and to determine how to adopt them in the context of forest sustainability.

Multiownership, multipurpose Douglas-fir landscape in Linn County, Oregon. Mosaic depicts varied ownerships and stand ages and very successful regeneration of harvested stands.

In spite of the complexity associated with society at large reaching agreement on the values to be achieved in forest management and metrics for measuring if management is successful at accomplishing the goals agreed to, this is exactly what many stakeholders have sought to develop over the past three decades, using the 1987 Brundtland Report as a very significant starting point in related discourse. And since the early 1990s, the political discourse regarding what constitutes sustainable forest management has gained real traction and is being implemented in forests around the world in the form of forest certification systems that have been initiated to address the challenges of defining and achieving the criteria for SFM on the ground. This article builds on the concepts underpinning sustainable forestry interpreted as the implementation of planning decisions and management actions required to meet the needs and desires of specific stakeholders for forest resource goods and services from a specific forest land area, without compromising the provision of these values to future generations. It involves land stewardship, as stemming from the writings of Aldo Leopold (1949), and management of forests and forest lands in ways and at rates that maintain their productivity, biodiversity, regeneration capacity, vitality, and potential to achieve, now and in the future, agreed upon ecological, economic, and social outcomes (Ferguson, 1996; Floyd, 2002; Helms, 1998; Landsberg and Waring, 2014; Oliver, 2003; Smith et al., 2009).

Concepts of sustainable forestry are based on three broad categories of criteria to be achieved and maintained:

environmental and ecological values;
economic values; and
social, political, and institutional values and frameworks.

According to international agreements that may be monitored at local to national and international scales, sustainable forestry includes:

- conservation of biological diversity;
- forest ecosystem health and vitality;
- maintenance of productive capacity;
- conservation of soil and water resources;
- maintenance of contributions to global carbon cycles;
- maintenance and enhancement of long-term socioeconomic benefits for societies;
- a legal, institutional and economic framework for forest conservation and sustainable management.

At this point in time, hundreds of millions of hectares of forests have been certified for being managed according to SFM principles and practices in Europe, North America, and around the world (see, eg, Rametsteiner and Simula, 2003; UNEP Green Economy). Major forest certification systems developed in North America include the Sustainable Forestry Initiative (SFI), the Forest Stewardship Council (FSC), the Canadian Standards Association (CSA) Sustainable Forest Management Standard, and the American Tree Farm System (ATFS). Internationally, the Programme for the Endorsement of Forest Certification is the largest forest certification system in terms of forest area (272 million ha), numbers of forest management certificates and number of chain of custody certificates (more than 17,000 companies); FSC is second largest system globally. These systems play a significant role in achieving sustainable forest management globally. All forest certification systems are based on the principles, criteria, and indicators expressed as the outcome of stakeholder engagement at local to international levels described above. It is important to note that the standards for SFM that each of these systems contain are under continual scrutiny; periodic reviews at approximately 5-year intervals lead to significant revisions to the standards; all are implicitly linked to and require compliance with forest policy and regulations in the jurisdiction containing specific forest management units. The evolution of these systems is under continual pressure to evolve as society's desire for and understanding of SFM evolves.

While there is currently a huge, dynamic international effort dedicated to managing forests sustainably, it is important to note that the probability of achieving the desired outcomes is unknown. Uncertainties are related to a number of factors, including

- the degree and direction of climate change.
- the severity and scale of natural disturbances, including:
  - fire;
  - windstorms;
  - insects and diseases;
- unforseen dynamics in economic, political, and social conditions that often play out at global scales with severe local impact.

Sustainable forest management systems should explicitly take such uncertainties into account and be based upon plans and programs to prepare for such, including application of adaptive forest management (see Raison, 2002). Adaptive forest management provides a rational, systematic framework for designing and implementing forest management and operations in the face of uncertainty about the outcome of our actions. As discussed in this article, uncertainty may be due to imperfect theoretical knowledge and cause-and-effect relationships or due to unexpected changes in climate, for example. Adaptive forest management involves engaging in sequential steps of "plan-do-check-review" and ultimately seeking continual improvement in the probability of achieving the desired outcomes sought in planning stages of management. This approach essentially involves operationally testing the hypothesis that a specific management action (plan) was valid by monitoring (check) the response of the forest ecosystem to a specific management operation (do) and seeking continual improvement by evaluating the adequacy of the original plan (review) and making adjustments where necessary in the next cycle of management.

In this article, we discuss ecology and silviculture for sustainable forestry and leave economic, and social and political considerations for companion articles (Brodie et al., 2016; Brown et al., 2016).

Ecology and Silviculture for Sustainable Forestry

In the following we discuss principles of forest ecology and silvicultural practices relevant for creating and maintaining resilient forests and specific recommendations in relation to uncertainties for sustainable forestry (Sensenig et al., 2013). These considerations can provide guidance for "on the ground" forest management in addition to the criteria and indicators of the common sustainable forestry systems (SFI and others). The examples and suggestions used are based on the authors' primary experiences in temperate forests of North America, New Zealand, and Nordic Europe, but are also influenced by our experiences in a variety of other forests of the world.

Sustainable forest management should be considered at relevant scales of forest area and ownership. From simply physical and ecological considerations watersheds and "ecoregions" (see below) would be useful land units to consider. However, in many landscapes "jigsaw puzzle" mosaics of land ownerships with varying management objectives and current individual forest stand conditions will likely constrain considerations of scale from the ideal to the practical. The practical unit of forest management is usually a "stand" occupying a few to tens of hectares (eg, Tappeiner et al., 2015; Helms, 1998).

For broad considerations, eg, management for biodiversity, large ungulates, foraging and nesting habitats for birds, and migration corridors, ecoregions are useful designations of land areas. An ecoregion is a "large unit of land or water containing a geographically distinct assemblage of species, natural communities, and environmental conditions" (Bailey, 2014; World Wildlife Fund, 2016). Boundaries of an ecoregion are not fixed and sharp, but rather encompass an area within which important ecological and evolutionary processes most strongly interact. In this context the scale of any forest management operation will make a difference in relation to management and forest conditions on adjacent lands because refugia and corridors for wildlife are significant at large scales, as are the effects of forest vegetation on climate (energy balance), and hydrology.

Within a given climatic and topographic setting, or ecoregion, forest growth and productivity result from combinations of the trees, shrubs and other organisms interacting with soils that provide reservoirs of water, nutrient elements and symbiotic microorganisms. These basic elements, vegetation-soils systems, provide the basis for the products and services humans expect from forests. Maintaining or restoring these ecosystem elements must be the most basic focus of sustainable forestry for resilient forests.

Forest Resilience

Forest resilience is the capacity of a forest ecosystem to return to its previous state after a significant, system-altering disturbance (eg, Boyle et al., 1997). Elements of resilience include stand composition and structure, wildlife habitats, hydrological functions and productive capacities of soils. Properties of soils that are key system characteristics in determining resilience are capacities to store water and nutrients, provide rooting space, recycle organic matter, provide organism habitats, and hydrological functions (eg, Boyle and Powers, 2013).

Older forests and mixed-species forests generally have more complicated structures than younger ones, potentially providing more resilience. Complex forest structures provide varying habitats for a variety of animals, from those that depend on dead trees for nesting, to those that browse plants in light gaps, seek out bark and wood boring insects, or consume root fungi. Structural complexity also favors plant diversity while reducing the momentum of wind and creating spaces for snow to accumulate in sheltered spots that retard melting. The presence of a mix of tree species offers resilience following attack from insects and disease

Original forest in northern California, USA, had been killed by fumes from a metal smelter; erosion followed. Current forest of planted ponderosa pines demonstrates resilience of soils and landscapes and successful reestablishment of a forest. (R. Powers photo).

(Ferrell, 1980). Resilience enables ecosystems to continue critical functions of primary production, transpiration, and nutrient cycling while stabilizing the land as roots of dead trees decay slowly and the boles and branches slowly release their stores of carbon and other nutrients while providing water-retaining buffers against erosion and desiccation. Forest ecosystem conditions that provide resilience, ie, that stabilize and buffer against irreversible change, should be objectives of prudent management plans for sustainable forests, for example:

- Provide buffers against environmental variation (climate, pollutants, fire, insects, disease) and potential for quick recovery from major disturbances; eg, enhance processes for storing carbon, nutrients, and propagules.
- Develop buffers against loss of habitat for native species, and provide corridors for movement. eg, maintain mixed-species forests.
- Develop buffers for the hydrologic cycle, ie, stand composition and structure for distribution of precipitation, moderation of stream flows, and minimization of erosion and landslides.

Species Adaptations to Disturbance

Trees and forests have evolved properties that withstand periodic disturbances. Here we consider examples of how different types of trees and forests have adapted to freezing, floods, drought, fire, and pests. Large gradients in tolerance to different types of disturbance exist within the gene pool of most species.

Freezing

Tropical, temperate, and boreal forests have evolved under climatic conditions where temperatures below freezing are, respectively, rare, common, and assured. Tropical trees have no adaption to freezing, while some temperate species can, during their period of dormancy, survive temperatures down to −42°C, the limits of super-cooling; boreal species, when properly prepared for winter, remove almost all water from their living cells (an extreme example is that some species have been shown to withstand the temperature of liquid nitrogen, −196°C).

Fire

Many tree species well adapted to frequent fire have thick bark and arrangements of branches and leaves that dissipate heat efficiently. Beneath the bark on some species lie adventitious buds that can produce new branches when older branches are injured. Others trees may die back to the ground but have burls or roots that initiate sprouts. Species that do not sprout may rely on seeds stored in serotinous cones that open at high temperatures; others produce seeds that remain buried in leaf litter until cracked open by high temperature (Caprio and Swetnam, 1996; DeBano et al., 1998; Tappeiner et al., 2015).

Drought

Many trees growing in drought-prone areas are less leafy than those in other forests. During drought they limit water loss by reflecting heat from waxy leaf surfaces dotted with scattered, tightly closed pores (stomata), or rapidly shed leaves. Some trees species avoid rather than tolerate drought by producing exceedingly deep roots that reach sources of groundwater unavailable to trees with shallower roots.

Floods

Forests growing on flood plains or in bogs or other places low in dissolved oxygen cope with flooding through use of less efficient, but reliable alternative biochemical pathways for keeping roots alive and functioning. Others produce exposed "knees" that allow air to diffuse down to roots below the surface of the water. Often floods deposit sediments, which eventually kill species not able to produce adventitious roots to colonize the new soil. Roots of thousand year-old coast redwoods (*Sequoia sempervirens* (D. Don) Endl.) in northern California have repeatedly colonized successive deposits of silt that now total more than 10 m deep.

Insects and Diseases

Although healthy forests are generally resistant to attack from native insects and diseases, drought, fire, windstorms, and exposure to pollutants may cause them to become vulnerable. At such times, large areas dominated by one species become particularly susceptible. This is true even of tall, older trees, because such trees must conduct water through a long pathway that causes photosynthesis to become less efficient, reducing the production of defensive compounds (Ferrell, 1980).

Introduced species of insects and disease are among the most dangerous invaders of ecosystems because native species have not evolved defenses. For example, bark sloughing by European silver fir (*Abies alba* Mill.) is a response to attack by wooly aphid, but when balsam fir (*A. balsamea* (L.) Mill.), a native of North America, is introduced or the aphid invades its home range, an epidemic results.

Examples for Implementing Buffers for Resilience

Maintaining species diversity and buffer functions should help preserve options for future generations.

Large, severe fires, common in some forests (eg, western United States), are often the result of accumulations of dead wood (fuel) from trees that had been growing at extremely high densities (numbers of trees per hectare); some such fires are perhaps exacerbated by climate change. In many cases in the western United States high stand densities and fuel accumulations have resulted from overzealous control of low intensity fires that would have reduced fuels to safer levels (Caprio and Swetnam (1996); Covington and Moore, 1994).

Dense forests are often predisposed to damage from severe wildfire and from insect infestations and mortality. Some large areas of dead forests (eg, lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) in central British Columbia, Canada, are likely the result of changing climate, including drought, high summer temperatures, abnormally warm winters, as well as risk-prone levels of high tree density. In young, less-dense, mixed species stands, the mortality may be less severe. Thinning in some stands could help establish or release already established seedlings and advanced regeneration (Filip, Fitzgerald, and Ganio (1999); Shatford et al., 2009; Korpela and Tesch, 1992), reducing need for intense operations to reestablish devastated stands.

On sites where the nutrient nitrogen (N) is limiting tree growth, and where seed banks of nitrogen-fixing plants are present, it may be possible to increase soil N and site productivity by careful use of fire and thinning. A light underburn to stimulate regeneration of nitrogen-fixers followed by thinning to stimulate their growth and nodulation could help replace N lost by wildfire (Bormann and Gordon, 1989). Care in burning and thinning is necessary to ensure that tree density is not reduced to the point that a dense, flammable understory is produced (Bailey and Covington, 2002). A moderately dense shrub community might also provide forage and habitats for wildlife.

Management Considerations for Resilient Forests

Principles to buffer for extreme changes are

- Maintain landscapes with large proportions of vigorous mixed species stands at low densities with low fuel loads to buffer the landscape against the severe effects of fire, wind and ice storms, and insects. In some mainly conifer forests "belts" of hardwoods could be strategically located across forest landscapes. These hardwood belts could, in some fire conditions, reduce fire rates of spread by providing "fuel breaks", as well as a diversity of habitats and possibly animal and bird travel corridors (Agee et al., 2000).
- Coordinate among forest management organizations, woods-worker contractors and public forest managers to provide a stable professional work force and maintain economical programs to thin stands; use the wood and treat fuels necessary to maintain stable buffers. Here cost is a major concern and forest managers should strive to help enable commercial yields from these activities whenever possible. Commercial yields of wood could help pay for treatments of small trees and shrubs to reduce potential fire damage in young stands.
- Coordinate landscape management among private and public ownerships. For example, public forests may best provide complex, late successional forests and large tracts of open, frequently burned forest that are resistant to fire, insects, wind and ice storms etc. Private forests may provide early successional habitat; regular commercial thinning of dense young stands could increase understory development and provide additional habitat (Bailey and Tappeiner, 1998).
- After severe fire, insect epidemic or windstorm, quickly assess potential progression of forest recovery. On many sites, without intervention, large, stable shrub communities will grow from seed banks, burls or sprouting roots in the soils of the burned

Mixed conifer stand in Oregon with varied structure and species composition providing varied animal habitats. This structure is extremely susceptible to severe, stand replacing wildfire. It is modestly resistant to insects and diseases because of its mixed species.

stands. These communities can retard or prevent the establishment of trees that could fix much more carbon (and provide commercial yields of wood) than would shrub communities (Powers et al., 2016; Zhang et al., 2008). Some patches of shrubs are probably desirable throughout a landscape for forage and cover. They can be strategically located to minimize their possible effects on fire spread and intensity.

- Buffer against loss of habitat for native wildlife and other species and provide corridors for movement.
- Within ecoregions locate areas that support less-common species: eg, old forests with complex structures, rare soil types, cold/frost pockets, wet areas. Ensure that the forests surrounding these areas are at appropriate densities (low to high) to increase habitat or protect from fire, provide corridors for wildlife movement into other habitats, buffer areas from temperature extremes, etc.
- Some forests contain native tree species currently threatened by pathogens. On sites where trees exhibit resistance to the pathogen, areas could be manipulated for natural regeneration, with the goal of proving increased resistance in natural populations. Some sites could also be used for testing survival and growth of nursery-produced trees bred for resistance. Fuel reduction should occur on all sites to reduce the probability of severe fire.
- Document population densities, tree fitness and responses to various environments and treatments. For example, an herbaceous species may be present and flowering in open environments, but not in shaded ones. A rare tree species might be present and vigorous in some sites and present and seriously infected with pathogens in others.

Buffer to Maintain the Hydrologic Cycle

Water from forested landscapes is an ecological service that must be maintained by forest management. Many of the forest stand treatments discussed above are compatible with maintaining water production from forests. For example, thinning and growing stands at low densities will reduce precipitation interception and transpiration by the forest canopy allowing more water to reach streams or below-ground water. In snow zones, regulating stand density by both by thinning individual dominant trees and patches and strips increases snow reaching the forest floor. Shade from trees reduces evaporation and sublimation of snow pack, delays and moderates timing of melting, and increases the amount of water reaching streams and aquifers (eg, experimental forests in Colorado and California, USA).

In very dry areas, reducing forest density along streams that are important water sources may increase water yield. As vegetation increases and water yields drop, additional density reduction could occur by thinning or cutting small patches in the forest. Ideally thinning/cutting would be designed to capture more snow and water from the snow as mentioned above. Increasing snow accumulation on north-facing slopes compared to south-facing slopes would likely increase water yield and prolong runoff as well.

Plantations of Forest Trees

Plantations of non-native species are grown worldwide, and many are more productive (m^3 wood/ha/year) than native species. Although less than 5% of the total world forest area, plantations account for nearly 35% of the world's wood products (FAO, 2011). Nonnative pines and species of eucalyptus make up a large percentage of the trees in plantations. Although initially lacking a normal complement of insects and diseases, nonnative plantations are difficult to sustain and may offer routes for movement of insects and disease into native forests. In plantations lack of species diversity and structural complexity limit varieties of habitats to support biological diversity.

Forest plantations require intensive management inputs, more similar to agriculture than to traditional management of native-species forests; eg, in plantations there may be intensive site preparation, weed control, fertilizer use, pest control, relatively frequent uses of heavy machines for harvest and planting with associated impacts on soils. Many plantations are on abandoned agricultural land and therefore seem aesthetically and socially acceptable as landscape components; this may be in contrast to places where plantations replace the visual appearance of native forests, whereas some plantations seem to be well integrated into complex landscape mosaics.

Detailed discussions of plantations are contained in numerous books (eg, Bauhus et al., 2010; Boyle et al., 1999). Even with the challenges of practicing sustainable forestry with plantations, they will remain essential for meeting societal demands for wood and other forest values.

Adaptation to Climate Change

Sustainable forestry should continue to be assessed across large geographical units that contain a distinct assemblage of species, native communities, and environmental conditions, as has been done by the numerous sustainable forestry certification systems now in place. The concept of ecoregions is useful in this context. Ecoregions define land areas containing refugia where species can survive for long periods even in the face of substantial change in climatic conditions. If climatic conditions change as much as predicted by some temperate forest species would have to migrate 100 km per decade in the rest of this century to remain in suitable

Plantations of non-native species in Scotland.

Intensively managed pine plantations as parts of mosaics of deciduous forest landscapes in southeastern United States.

habitats. Protection of refugia will help, but assisted migration will be necessary too, given that natural rates of potential migration are generally less than 2 km per decade. With rapid climate changes (Chmura et al., 2011), rates of disturbance are likely to increase. And, growth of forests of current composition may decrease. If so, this would alter expectations for commercial forests with attendant economic implications.

Without knowing the magnitude and rate of climate change, we can only speculate on its effects on forest productivity. Repeated forest inventories that measure stand growth and mortality are needed to monitor effects. For example, we expect that on dry sites, in comparison with more moist sites, productivity is apt to decrease most, from a combination of increased moisture stress leading to decrease in stand photosynthesis combined with the effects of insects and diseases on weakened trees (eg, Donner and Running, 1986). On sites with deep soils that can store considerable water, moisture stress may not be as important as on dry sites, but pathogens or inability of trees to meet chilling requirements may become important. On moist sites foliar pathogens may become more important in a warmer climate.

To envision ways that climatic warming might influence a population of trees, we contrast two hypothetical situations in the Northern hemisphere: the first, a flat plain, and the second, the slope of a mountain extending from the edge of a valley upward to the current elevational tree line.

As the climate warms, a species on the plain will find conditions at its northern limit becoming more favorable for growth, and less so at its southern limit. Similarly, on the mountain lower slope conditions will become less favorable, and those slightly above timberline more favorable. On the plain, the length of day each month may differ substantially at the species' geographic latitudinal limits (longer day length at higher latitude). On the mountain with no change in latitude, there would be no need for physiological adjustment to match day-length-controlled bud-break and dormancy for growth in new set of conditions. This might not be the case for physiological processes that are strongly temperature influenced.

With changes we might expect a shift in the distribution of species, given enough time for seeds to be spread by various mechanisms (birds, vehicles, wind) and pollinators to follow. The time required for natural movement (migration) of tree species, however, would be much longer than that for which suitable conditions for some species are predicted to shift northward and up slope over the next 30-50 years. This means that forest managers should consider helping some species to migrate northward (or upward) while trying to keep those populations at lower latitudes viable as long as possible (Conckle, 1973).

As growing conditions become harsher, it takes longer for trees to grow to reproductive age, and also longer to grow to a size that is commercially valuable. This presents a dilemma for forest managers: to select genetic representatives from a species population that might be most suited to thrive under climatic conditions in 30–50 years but that might not survive as seedlings or young trees under present conditions. If foresters were to select the fastest growing representatives of a species that grows well on a fairly wide range of sites, they might well find that their selections would have less resistance to native diseases or to the mechanical forces of wind, ice, and snow than those populations growing more slowly. Change is happening so rapidly that the most prudent choice is to maintain as much genetic variation as possible, with the most buffered forests likely being those with a half dozen or more species.

If climatic conditions change sufficiently, in some ecoregions and sites forests may disappear and be replaced by steppe, prairie, or desert vegetation. In recognizing climate change the goal of sustainable forestry is to accommodate ecological conditions through selected silvicultural practices and to take advantage of disturbances that favor natural regeneration and the perpetuation of forests.

Conclusion

Achieving sustainable forestry entails a complex set of considerations and processes. In addition to managing forests to comply with current systems of certifying sustainable forests are the challenges presented by impending climate change and unpredictable "disasters", such as severe fire, insect and disease outbreaks, that can devastate a forest or large forested landscape. Recognizing aspects of forest resilience at species, stand and landscape levels, knowing options for silvicultural treatments of forests, and planning for contingencies will contribute to the continuing quests for sustainable forestry.

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