REVIEW ARTICLE

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silviculture

Silviculture in the United States: An Amazing Period of Change over the Past 30 Years

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The practice of silviculture is continually evolving in response to a multitude of social, economic, and ecological factors. In 1986, the *Journal of Forestry* published a series of papers that reflected on changes in silviculture in the United States from the 1950s to 1980s and predicted how silviculture might develop in the next 30 years. We revisit the fundamental changes influencing the practice of silviculture since 1986; we explore how contemporary silviculture may evolve in the coming years in response to changing ownership structures on industry lands, declining research investments, and an increasing suite of stressors affecting forests, including invasive species and climate change. Many of the changes in management context and forest conditions occurring over the last 30 years were not anticipated and have resulted in an increase in silvicultural systems that integrate ecological and noneconomic social values on public lands. Many advances reflect a legacy of investment in silvicultural research and development in the 1970s and 1980s.

Keywords: forest history, forest industry, variable retention, megafires, invasive species

In 1986, a series of six papers were published in the *Journal of Forestry* on the practice of silviculture in the United States. The series, "Silviculture: The next 30 years, the past 30 years," was initiated with an overview article (Oliver 1986) and included five additional papers focusing on the major forest regions of the United States (Benzie et al. 1986, Boyce et al. 1986, Long et al. 1986, Seymour et al. 1986, Tappeiner et al. 1986). Each article included reflections on changes in the practice of silviculture from the 1950s, its status in the mid-1980s, and changes the authors thought might occur in the subsequent 30 years in each region. Collectively, this series provided an important body of knowledge on the maturation of the practice of silviculture in the United States and the various economic, social, and ecological drivers expected to affect the nature of silviculture applications in the future.

Many of the predictions from this series regarding the future of silviculture were reflective of changes in social and ecological conditions and technology manifesting in the 1980s. For example, the increasing influence of public involvement and forest regulations over forest management and the growing importance of nontimber benefits were identified as future drivers of a shift from clearcutting-based systems in several regions, including the Pacific Northwest and Lake States (Benzie et al. 1986, Tappeiner et al. 1986). The continued maturation of forest conditions in the northeastern United States was expected to increase the need for future regeneration harvests and young stand tending treatments (Seymour et al. 1986), whereas predicted increases in the area of overstocked conditions in the Intermountain West would place a greater emphasis on density management to reduce associated forest health issues (Long et al. 1986). Future productivity gains in plantation silviculture were also anticipated via tree breeding and increased application of vegetation management in the South and Pacific Northwest (Boyce et al. 1986, Tappeiner et al. 1986). Advances in forest and stand models were expected to increase our ability to evaluate the outcomes of different silvicultural prescriptions (Benzie et al. 1986).

Elements of these and other predictions made 30 years ago are certainly reflected in contemporary silviculture in the United States; however, the magnitude of change in both the context for management and factors influencing the practice of silviculture could not have been imagined. Our objective is to use the 30th anniversary of this series as an opportunity to revisit and reflect on the fundamental changes influencing the practice of silviculture since 1986. This includes highlighting the major changes in

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This article uses metric units; the applicable conversion factors are: square meters (m^2): 1 m^2 = 10.76 ft^2; hectares (ha): 1 ha = 2.471 ac.

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management context, research investments, forest conditions, and technology that have occurred over the last 30 years and the resultant impacts on silvicultural systems currently applied. We conclude by identifying the factors most likely to influence the ways in which silviculture is practiced over the next 30 years in response to current and emerging threats and management objectives.

Changes in Management Context

Over the last 30 years, the context of forest management in the United States has gone through one of its most dynamic periods in history. Record fuel load accumulations, extreme fire events (megafires), and epidemic insect outbreaks, often as a result of extended drought, fire exclusion, and management policies (Williams 2013), have affected forests, especially in the West. In addition, during this period, changing ownership and land tenure patterns, rural land urbanization, increased globalization of forest markets, decreases in demand for wood products, operational-scale adoption of forest certification standards and best management practices (BMPs), and conservation easements have all influenced silvicultural decision-making. With the exception of private, intensively managed forestlands, forest management objectives have been broadened and go beyond the historical importance of managing for sustained timber yield. Contemporary silvicultural prescriptions for a range of land ownerships may also include elements of invasive species management; conserving old forest ecosystems and riparian reserves; enhancing water quantity and quality; recreation; esthetics; augmenting biological diversity; and the restoration of endangered, threatened, and sensitive species and ecosystems.

In 2012, the area of forested land in the United States was estimated at 766 million acres, with approximately 68% classified as timberland (US Department of Agriculture [USDA] 2014). Approximately 70% and 30% of the land in the West falls under public and private ownership, respectively; this ratio reverses in the East, where public ownership represents approximately 19% and private ownership 81%. Although the total forested area has historically remained fairly stable in the United States, the character, distribution, and ownership patterns of these lands have continued to change and influence the management objectives and silvicultural practices being used. For example, approximately 10% of all forestlands are "reserved forests" and are not being actively managed for timber production. Over the last 30 years, reserved forests have nearly doubled from approximately 37 million ac in 1987 to 74 million ac in 2012, with the greatest increase occurring in the West (USDA 2014). In the Northeast, where private ownerships predominate, recent assessments of forest cover indicate slight losses to other land uses after more than a century of consistently gaining forestland area (Drummond and Loveland 2010). Forest area has slightly increased overall during this period in the Southeast because of the afforestation of agricultural lands; however, there have still been localized losses in forest area to urban and residential development (Wear and Greis 2013).

Other changes, especially on federal lands, have also emerged. For example, the Northwest Forest Plan, established in 1994, was created to form a coordinated set of management directions and guidelines for 24.5 million acres of federal land (e.g., USDA Forest Service, US Department of the Interior) to conserve biodiversity and meet endangered species habitat needs for the northern spotted owl (*Strix occidentalis caurina*; Thomas et al. 2006). Implementation of this plan has proven difficult, leading to recent concerns over declines in young forest habitat due to a lack of regeneration harvests on federal lands (Franklin and Johnson 2014); this was certainly unanticipated for the region 30 years prior (Tappeiner et al. 1986). The unexpected, broader decline in timber harvests on federal lands in many portions of the West over this period has also led to a general reduction in milling capacity (Keegan et al. 2006), thus limiting opportunities for practicing silviculture. This includes limiting the application of much-needed fuel reduction and density management treatments for addressing current wildfire and forest health concerns in many of these areas (Rummer 2008), a situation targeted through legislation including the Healthy Forests Restoration Act of 2003. Finally, federal lands in other regions, such as the Southeast, have seen a dramatic shift in management approach from clearcutting-based systems in the 1980s to now using a range of even and multiaged silvicultural systems to address ecosystem management objectives (O'Hara 2014, USDA 2013a).

Changes associated with an expanding urban influence have also affected the context of silvicultural practices during this period. Urban lands increased from 2.5% of the total land area in 1990 to 3.6% in 2010, with forested lands in rural counties declining by 17% in the past 15 years (USDA 2014). The wildland-urban interface (WUI) has particularly become a source of human–environment conflicts (e.g., wildfire threats, habitat fragmentation, biodiversity declines, and exotic species invasions; Radeloff et al. 2005, Stein et al. 2013). Accordingly, management prescriptions have required modification. For example, despite the ecological importance of using prescribed fire as a tool

Management and Policy Implications

The application of silviculture at any point in history reflects various aspects of the ecological, economic, and social conditions during that period. We present a review of the changes in management context, research investments, forest conditions, and technology that have occurred over the last 30 years and their influence on how silviculture is currently practiced. The summary of changes during this highly dynamic period and their influence on silviculture across different regions of the United States will be useful to forest managers and policymakers for anticipating how changes in ownership, increases in the scale and severity of wildfire, and proliferation of invasive species will affect how silviculture is practiced in the future. Changes in the nature of industrial ownerships over the past 30 years will likely continue to reduce levels of investment in silvicultural treatments in regions where productivity rates are too low to generate short-term returns, whereas investment in intensive cultural practices, such as deployment of genetically improved stock, competition control, and fertilization, may continue in more productive regions such as the Southeast. Growing concerns regarding changing environmental conditions, disturbance, and invasives could lead to an increasing application of silvicultural systems focused on conferring resistance and resilience to their impacts across ownerships. The dramatic declines in research investments observed over the past 30 years will challenge our ability to generate the applied knowledge necessary for addressing these changes.

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for fuels reduction, and the restoration and management of fire-adapted ecosystems, public tolerance for this tool has changed, especially at the WUI (Haines et al. 2001). Public health and safety concerns, roadway visibility, liability issues, and various federal and state regulatory statutes associated with smoke management and air quality have challenged prescribed burning as a viable management option. In response, new smoke management guidelines have been specifically developed for WUIs to aid management decisions by burn professionals in smoke-sensitive areas (Wade and Mobley 2007).

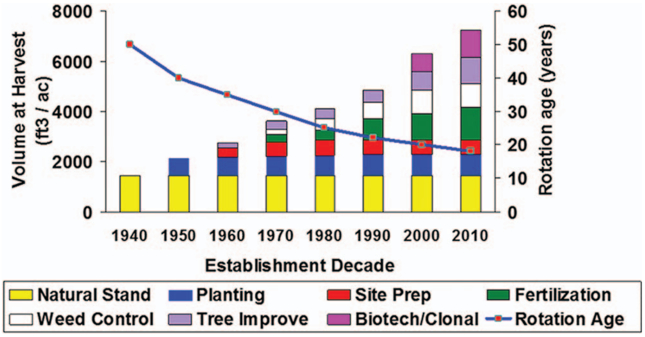

Figure 1. Contributions of silvicultural practices to productivity improvements and rotation lengths in managed southern pine stands. Redrawn from Fox et al. 2007.

Globalization of the private forest products industry has resulted in significant changes in business strategies, priorities, organizational structures, and concomitant modifications in landownership configurations (Carter et al. 2015). Consolidation of forest products companies began occurring with regularity in the 1980s and has continued to the present to aid global market competitiveness with divestiture of timberland assets, in many cases to institutional investors (Bliss et al. 2010, Zhang et al. 2012). This has led to the growth of Timberland Investment Management Organizations (TIMOs), which acquire, manage, and sell these timberlands, with the focus on maximizing growth in value of timberland assets. At the same time, many traditionally vertically integrated forest products companies have converted to publicly traded Real Estate Investment Trusts (REITs). The 2016 merger between Weyerhaeuser and Plum Creek Timber Company, Inc., formed the largest REIT in the United States, with more than 13 million acres of timberlands and 38 wood product manufacturing facilities.

The shorter planning horizons of these ownership types relative to previous corporate ownerships (e.g., 7–15 years for TIMOs; Fernholz et al. 2007) has changed the level of investment in silvicultural treatments. In some regions, such as the Southeast, REITs and TIMOs tend to use similar silvicultural treatments and prescriptions developed earlier by the forest industry, focusing on conifers and high-yield management regimes (e.g., site preparation, deployment of genetically improved seedlings, competition control, soil nutrient management, thinning, and reduced rotation lengths compared with publicly owned forests; Figure 1). However, investments in practices such as forest fertilization and precommercial thinning occur earlier or may not occur at all in the investment period because they must add tangible value to the asset before it is transferred to another owner or the stand is harvested. In other regions, such as the Northeast and Lake States, this shift in ownership has led to an overall decline in silvicultural investments given the lower productivity in these regions and correspondingly longer time periods required to generate returns (D'Amato et al. 2009, LeVert et al. 2007). In addition, the central focus of REITs and TIMOs on the highest and best uses of forestland from an economic perspective has resulted in the loss of productive lands to development and fragmentation of historically larger ownerships (Gunnoe and Gellert 2011).

The environmental movement of the 1970s had a profound impact on forestry and silvicultural decision-making described in the original "30 years" papers; however, BMPs, third-party forest certification, and the concept of conservation easements did not materialize in earnest until the 1990s, largely in response to escalating social and environmental concerns regarding the stewardship and sustainable management of forests on public and private lands (Carter et al. 2015). The changes that ensued were steady, purposeful, and in many ways historic. They led to the creation of forestry legislation in many eastern states in the 1980s and early 1990s (e.g., Massachusetts in 1983, Maine in 1989, and Connecticut in 1991) that built on the early forest practices acts created in previous decades (e.g., California in 1945, Oregon in 1972, Idaho in 1974, and Washington in 1975) in response to concerns over reforestation practices, the sustainability of harvest levels, and the passage of landmark environmental federal legislation (i.e., Clean Air, Clean Water, and Endangered Species Acts). Similarly, the rise of large conservation ownerships through the placement of easements on divested industrial timberlands during the 1990s and 2000s has created a new ownership type in large working landscapes that applies silviculture to meet a diversity of objectives ranging from biodiversity conservation to carbon storage (Meyer et al. 2014).

During the past 30 years, BMPs have found widespread adoption as science-based guidelines for silvicultural operations (Cristan et al. 2016), including the implementation of national BMPs and monitoring approaches on all US National Forest System lands in 2013–2014 (Carlson et al. 2015). BMPs have a central focus on protection of water quality, and as such they commonly address maintenance and construction of forest roads, timber harvesting, skid trails, reforestation, site preparation, streamside management zones, stream crossings, and the protection and management of wetlands (Cristan et al. 2016). In some cases, BMPs also address certain wildlife habitat values during forestry operations (e.g., Florida Department of Agriculture, and Consumer Services 2014), including provisions for the retention of living and dead trees. Because of their success, normal silvicultural activities have been exempt from permitting requirements under Sections 404 (dredge and fill) and 402 (discharge of pollutants) of the Clean Water Act. A recent report assembled by the National Association of State Foresters stated that BMP implementation rates averaged 91% nationwide (National Association of State Foresters 2015).

In contrast to 30 years ago, third-party forest certification programs have found prominence on today's forested landscape. Within the United States, the three major certification programs include the Sustainable Forestry Initiative (SFI; established in 1995), the Forest Stewardship Council (FSC; established in 1993), and the American Tree Farm System (ATFS; established in

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1941). A fourth, the Programme for the Endorsement of Forest Certification, is the world's largest certification system and through its endorsement has provided international recognition to the SFI and ATFS forest management standards. Recent statistics suggest that private landowners in the United States have certified approximately 118 million acres of timberland (~20%), with 5% by ATFS, 7% by FSC, and 12% by SFI (American Forest & Paper Association 2016). From a silvicultural perspective, all three programs share similarity and credibility toward advancing sustainable forest management and water quality protection, but some programmatic and regional differences exist (i.e., distinguishing plantations versus natural stands, adjacency, stand green-up requirements, chemical usage for pest and competition control, harvest size, and retention requirements in openings; Mendell and Lang 2012). To date, although some state and municipal timberlands have been certified by FSC and/or SFI, no federal lands with timber harvest activities (i.e., USFS, Bureau of Land Management) have received third-party certification. In addition, recent years have witnessed some ownerships deciding not to renew certification given the costs, increasing requirements, and lack of direct market benefits (e.g., McDermott et al. 2006).

Changes in Research Commitments

The application of scientific knowledge developed on the practice of silviculture over the past 30 years has resulted in tremendous gains both in the health and productivity of managed forests. This has also enhanced our ability to balance a diversity of economic, ecological, and social objectives in managed landscapes. For example, research on soil fertility and response to fertilization has a long history in forestry (Gessel et al. 1965, Walker 1960). With the creation of research cooperatives in many regions beginning in the 1960s (Inland Empire, Pacific Northwest, Southeast), long-term industry–university research partnerships were developed to examine the feasibility and outcomes of forest fertilization in plantation management (Carter et al. 2015). In 1988, midrotation fertilization in the Southeast was applied to approximately 15,000 ac each year; by 2000, fertilization had increased to more than 1 million ac per year (Fox et al. 2007). Although there are many factors behind this increase in fertilization, a key factor was that forest fertilization research begun in the 1960s became widely applied in the 1990s. An important outcome of this research was the ability to accurately identify sites and stands that consistently respond to fertilizations (Fox et al. 2007).

These and other significant research investments in silviculture over the last 30 years, including large federal investments in operational-scale silviculture studies examining the impacts and outcomes of ecological silviculture practices such as variable retention and natural disturbance emulation (e.g., Aubry et al. 2009, Seymour et al. 2006), will become less common over the next 30 years because of changes in industry and declining state and federal research budgets. In particular, the consolidation of the forest industry and the creation of REITs and TIMOs has challenged the strong applied research dimension of university–industry forestry cooperatives in the South and elsewhere (Wheeler et al. 2015). These changes have resulted in fewer members to conduct and support research, less expendable research capital, reduced land access and in-kind support for installing and monitoring long-term experiments, greater likelihood that lands containing long-term experiments may be sold, and a reduction in the number of PhD-level scientists in forest companies. Likewise, the ability to maintain and enhance the long-term silviculture studies established by the US Forest Service (USFS) on Experimental Forests and Ranges and elsewhere continues to decline. As federal research budgets dwindle, the number of research positions has decreased, and the increasing costs for addressing large-scale wildfires in the western United States and elsewhere commonly threaten what research budgets do remain. Research universities are also experiencing a decline in their applied research capability (O'Hara and Salwasser 2015), coincident with declining USFS and McIntire-Stennis support for applied research (Bullard et al. 2011), and the loss of silviculture faculty positions through disciplinary mergers at some institutions. Without a similar long-term commitment to research by the forestry community (e.g., TIMOs, REITs, USFS, universities), one must wonder whether future advancements will be as dramatic as in the past (Figure 1). After all, research investment is the foundation for modifying old and developing new management guidelines. It is also central to our goal of developing site-specific silvicultural prescriptions.

Changes in Forest Conditions

Changes in forest and environmental conditions over the past 30 years have increased both the number and magnitude of challenges facing silviculturists in meeting contemporary management objectives. Some of these changes, including US-wide increases in growing stock (USDA 2014), could have been predicted based on forest conditions and harvesting rates in 1986; however, other changes, including the prevalence of invasive species and the magnitude and severity of disturbance affecting US forests, were largely unexpected.

The increasing prevalence of high-density conditions in western forests and the associated forest health and fire risks were identified as an important future driver of silvicultural activities 30 years ago (Long et al. 1986); however, the severity of the impacts of these conditions on current forest dynamics was not anticipated. Two years after the publication of the "30 years" series, Yellowstone National Park would experience what is now collectively referred to as a "megafire" (Adams 2013). These large-scale events now affect more than 490,000–1,400,000 ac of forest each year (Hicke et al. 2016). Likewise, the mountain pine beetle (*Dendroctonus ponderosae*) and other bark beetles have become a dominant disturbance agent on the landscape because of both the prevalence of low-vigor, high-density stand conditions and warmer winter temperatures resulting in outbreaks killing trees across more than 240,000 ac per year (Hicke et al. 2016). The increase in the extent and severity of natural disturbances in the West and other regions of the United States has increased the emphasis on silvicultural regimes that anticipate disturbance impacts by encouraging the development of resistant and resilient stand structural conditions (DeRose and Long 2014). However, the challenges of applying these treatments at a scale that can reverse the impacts of decades of regional fire suppression on wildfire behavior has led to a parallel emphasis on integrating the management of postdisturbance legacies into salvage treatments (O'Hara and Ramage 2013). Moreover, these increases in wildfire frequency and severity have the potential to eliminate forested conditions in a given region (Lindenmayer et al. 2016), creating an increasing need for reforestation ap-

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proaches for addressing the novel conditions left in their wake.

Non-native, invasive plant species have become a pervasive component of most forested regions of the country, significantly affecting diversity and productivity and increasing costs associated with regeneration activities. Although many species, such as European buckthorn (*Rhamnus cathartica*), Chinese tallow (*Triadica sebifera*), and Japanese honeysuckle (*Lonicera japonica*), have existed in agricultural and ornamental settings in the United States for more than a century, the extent of their impact has substantially increased. Invasive plant species now exist across a substantial portion of forestland in the United States (Oswalt et al. 2015), including 9% of all forested acres in the South (Miller et al. 2008). The signing of Executive Order 13112 in 1999 acknowledged this increase and its ecological and economic impacts and has established invasive species control as a management priority across US National Forests (USDA 2013b). Likewise, vegetation management efforts on commercial timberland are increasingly focused on limiting the impact of non-native species, such as cogongrass (*Imperata cylindrica*) and broom species (*Cytisus* spp), on plantation establishment and stand productivity (e.g., Harrington 2014, Minogue et al. 2012). Given the costs associated with widespread control and significant lags that often exist between species introduction and widespread invasion (Crooks 2005), non-native plant species will remain a significant challenge in the future, particularly as changes in climate and land use increase the potential for future invasions (Diez et al. 2012).

As with non-native plant species, introduced insects and diseases affect an increasing number of economically and ecologically important tree species across the United States. The greatest concentration of introduced species is in the Northeast (Liebhold et al. 2013); however, the exponential increase in the volume of US global imports since the 1980s has contributed to a dramatic expansion in the number of species affecting forests across the country (Lovett et al. 2016). The ability of many of these species, including hemlock woolly adelgid (*Adelges tsugae*), sudden oak death (*Phytophthora ramorum*), emerald ash borer (*Agrilus planipennis*), and laurel wilt (*Raffaelea lauricola*), to effectively eliminate a given tree species has resulted in significant alterations to the structure, composition, and function of numerous forest types (e.g., Ellison et al. 2005, Herms and McCullough 2014, Ramage et al. 2011). In some cases, this expanded suite of invasives is affecting forested regions already affected by historic species introductions (Liebhold et al. 2013), such as chestnut blight (*Cryphonectria parasitica*) and beech bark disease (*Cryptococcus fagisuga* + *Nectria coccinea*). These dynamics limit options for tree species selection when developing prescriptions to address new threats. Eradication of these introduced pests is generally infeasible, with integrated pest management approaches now increasingly focused on silvicultural strategies ranging from preemptive removal of vulnerable species to promoting stands composed of a greater component of nonhost species (Looney et al. 2015, Waring and O'Hara 2005).

Changes in disturbance regimes, host population structure, and environmental conditions have also led to increasing effects of native plants, insects, and pathogens on forest health in various regions of the United States (Royo and Carson 2006, Weed et al. 2013, Wyka et al. 2017). As with non-natives, these stressors have created novel conditions over large portions of the landscape that require similar integrated and adaptive approaches to those applied to non-native species. One success story over the past 30 years with addressing the impacts of native forest health threats has been the development and deployment of fusiform rust-resistant loblolly pine in the southeastern United States, dramatically reducing the incidence of this issue across the region, particularly in plantation silviculture (Schmidt 2003, Vergara et al. 2007). Likewise, widespread thinning treatments in the southeastern United States have also been successful at reducing the hazard of southern pine plantations to southern pine beetle (SPB; *Dendroctonus frontalis*) infestation at the stand and landscape scale (Nowack et al. 2015). However, in acute outbreak cases of SPB, local market conditions (e.g., regional timber supply, operable stumpage volume and quality) may affect the timeliness of silvicultural interventions, resulting in unintended consequences. In concert with the general success with reducing SPB hazard in the Southeast has been an unprecedented range expansion of SPB into the northeastern United States over the past 2 decades, creating significant challenges to the conservation of pine-barren communities in this region (Weed et al. 2013).

A concern raised regarding future forest conditions 30 years ago was the long-term impacts of atmospheric deposition on forest health and productivity (Oliver 1986). Increased nitrogen and sulfur deposition continues to influence soil and forest health conditions in certain regions, such as the Northeast (DeHayes et al. 1999); however, levels of deposition have declined substantially over the past 15 years because of the Clean Air Act of 1971, resulting in healthier forest and aquatic communities in many regions. Now, the primary abiotic factor most broadly affecting recent changes in forest conditions is a shift in climate conditions toward warmer temperatures and greater extremes in precipitation in many areas of the United States (Melillo et al. 2014). Increasing atmospheric carbon dioxide concentrations are expected to increase future forest productivity (e.g., Groninger et al. 1999). However, the interactive effects of warmer temperatures (e.g., Figure 2) and prolonged droughts with increases in host suitability, forest fuels, and stocking have amplified the scale and severity of disturbance occurring in contemporary landscapes (Millar and Stephenson 2015) and may overwhelm these productivity gains in many regions. The uncertain nature of these interactions and the increasing impacts of invasive species on many forests have introduced a high degree of uncertainty regarding our expectations of future forest conditions that was largely absent from projections of future trends in 1986. Silvicultural treatments, including manipulating stand density to reduce future drought impacts (Clark et al. 2016, D'Amato et al. 2013) and increasing the representation of species likely adapted to future environmental conditions through planting and regeneration harvests (Pedlar et al. 2012), have been suggested as approaches to address this uncertainty; however, an understanding of their effectiveness at affecting broad-scale changes in environmental conditions on future forests remains limited.

Advances in Technology

Many of the changes in management context and forest conditions described above have presented unexpected challenges to modern day silviculture; however, there have been extraordinary advances in research and technological development in the last 30 years that have profoundly benefited silvicultural practice. Changes in the silviculturist's toolkit include such breakthroughs as the ways that stand and landscape data are captured and analyzed, near site-specific characterizations of fertilization response, availability

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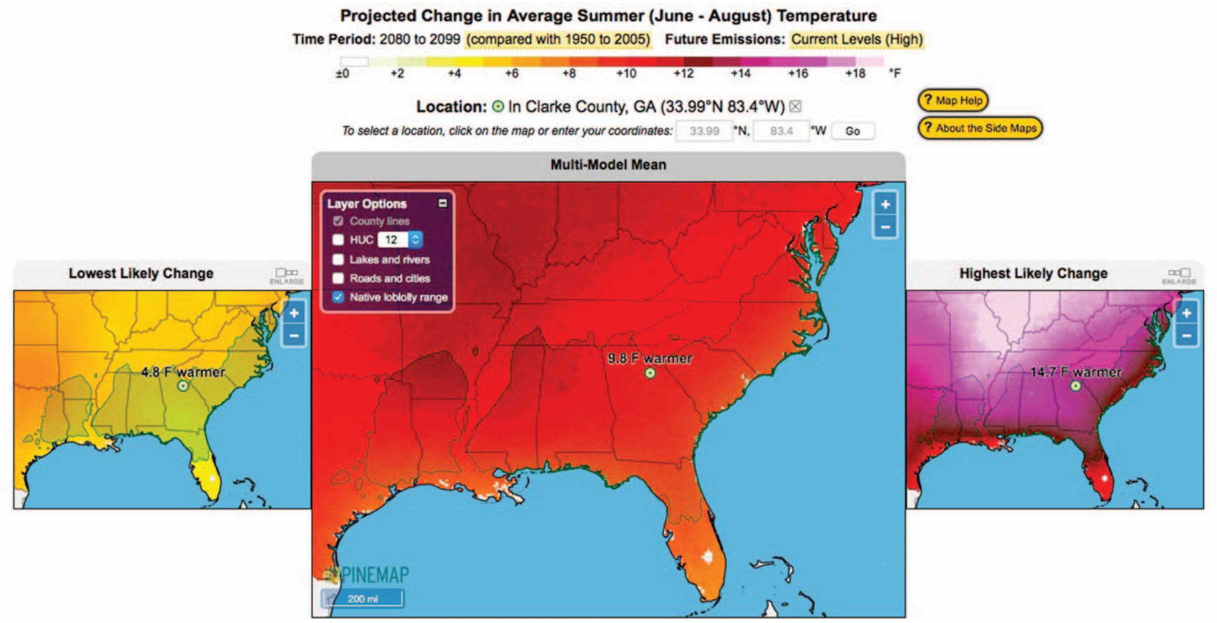

Projected Change in Average Summer (June - August) Temperature

Time Period: 2080 to 2099 (compared with 1950 to 2005) Future Emissions: Current Levels (High)

Location: In Clarke County, GA (33.99°N 83.4°W)

To select a location, click on the map or enter your coordinates: 33.99 °N, 83.4 °W Go

Layer Options

☑ County lines

☐ HUC 12

☐ Lakes and rivers

☐ Roads and cities

☑ Native loblolly range

Figure 2. Output from a tool in PINEMAP's Decision Support System that contains future projected changes of average summer (June–July–August) temperature, highlighting the multimodel mean (center map) across 20 downscaled global climate models as well as the lowest and highest likely outcomes, which are 2 SD below (left map) and above (right map) the multimodel mean, respectively. The map represents future conditions expected for end of century (2080–2099) under a Representative Concentration Pathway of 8.5 or high greenhouse gas concentrations by end of century with a total radiative forcing of 8.5 W/m^2 by 2100. The shaded area represents the natural range of loblolly pine (*P. taeda*), and Athens, GA is used as a reference point for making comparisons for the different climate scenarios.

of genetically improved planting stock for several commercially important species, and development of improved harvesting and handling equipment. Another important change is the ability to rapidly share and exchange ideas and research on silvicultural practice through the Internet and other digital media.

Advances in computer technology have fundamentally changed our approaches to the development and analysis of silvicultural alternatives and land management decision-making. Silviculturists today have at their disposal a suite of tools to use in the prescription process that did not exist 30 years ago or were not yet operational. Some of these changes, such as global positioning systems (GPS), relational databases, mapping technologies, visualization software, growth and yield simulators (Dixon 2002), and online access to national forest inventory data (i.e., USDA Forest Service's Forest Inventory and Analysis Program) are now so important and pervasive in assisting with silvicultural decision-making that we almost take them for granted. Nonetheless, the increased use of electronic media associated with these technological advances has led to significant decreases in demand for pulp and paper (Latta et al. 2016) and reduced availability of markets for low-grade materials in many regions (Woodall et al. 2011). These changes in demand, in conjunction with recent economic downturns, have collectively reduced the capacity for practicing silviculture across much of the United States (Woodall et al. 2011).

The nature of remote sensing applications in silviculture practice has already fundamentally changed and continues to rapidly evolve. Reliance on traditional photo interpretation for vegetation classification and forest stand delineation has to a large extent been supplanted by digital imagery, most of it from satellites. This evolution is reflected in the fact that although forestry students typically receive excellent training in remote sensing, they have limited, if any, exposure to photogrammetry. Light Detection and Ranging (LiDAR) is a breakthrough remote sensing technology with considerable potential application in forest inventory, planning, and silviculture (Dubayah and Drake 2000, Hudak et al. 2009). It is likely that LiDAR and similar developing technologies, such as unmanned aerial vehicles, will in the near future be routinely used by foresters as a standard forest inventory and monitoring tool and for planning road layout and other aspects of harvest operations.

A fundamental application of geographical information systems (GIS) software is the creation of maps, but the breakthrough for silviculturists lies in the analytical power that results from the juxtaposition of multiple spatially explicit data layers in a comprehensive GIS. Moreover, the use of GIS to plan and implement timber harvests, including the use of in-cab GPS units for equipment operators, has increased the efficiency and precision of applying silvicultural treatments.

The availability of interactive, web-based decision support systems for guiding silvicultural planning in the context of future environmental conditions and stressors has greatly expanded over the past decade as concerns over global change have increased. For example, the PINEMAP (Pine Integrated Network, and Adaptation Project; http://pinemap.org) research project has focused on adapting forest management approaches to increase the forest resilience and sustainability of loblolly pine (*Pinus taeda*) under variable climates and has produced a map-based collection of climate and forest productivity web tools designed to provide region-wide information on likely future climate risks, opportunities, and impacts at a watershed scale (Figure 2). In the upper Midwest and Northeast, the Climate Change Response Framework (http://forestadaptation.org/) has developed a series of forest adaptation resources for assisting

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landowners in developing prescriptions to address projected climate change impacts in these regions. Decision support tools such as these will continue to provide utility in transforming research results into a context that allows natural resource professionals and clients to make informed land management decisions.

In addition to the technological advances that now greatly facilitate silvicultural planning, the last 30 years have seen tremendous advancements in the development of the harvesting and handling equipment now used to implement different silvicultural activities. In particular, harvesting systems have become increasingly mechanized, with feller bunchers and cut-to-length (CTL) processors now the most common systems in areas with gentle to moderately steep terrain. This mechanization has increased productivity and safety of harvesting operations and lowered site impacts relative to traditional skidder-based systems. In addition, the greater control in felling direction and lack of skidding with CTL limits the levels of residual damage in thinning and selection harvests, thereby increasing the overall effectiveness of these practices (Huyler and LeDoux 1999). Nonetheless, the upper size limits for these processors (~22–24 in.; Huyler and LeDoux 1999) limit their applicability to certain stand conditions and silvicultural treatments. In addition, an increasingly aging logging workforce and declines in the number of forestry field staff may limit future opportunities for carrying out silvicultural treatments in many regions (Egan and Taggart 2004).

A technological advancement and associated shift in silviculture, which was anticipated 30 years ago, has been the development and widespread deployment of genetically improved planting stock (Boyce et al. 1986, Fox et al. 2007). Increases in end-of-rotation yield were on the order of 10% for southern pine plantations established with planting stock produced from first-generation seed orchards compared with stock from wild seed. Additional gains from second-generation orchards might be on the order of 20%. The gains associated with tree improvement are not just increases in yield; they include stem straightness, wood quality, and disease resistance (Fox et al. 2007). A silvicultural challenge during plantation establishment with improved stock is the risk of unwanted natural regeneration diluting potential gains—an issue recognized 30 years ago (Boyce et al. 1986, Tappeiner et al. 1986). In addition, the successful establishment of loblolly pine plantations across a significant portion of the southeastern United States has resulted in greater levels of hybridization with other species, including shortleaf pine (*Pinus echinata*), creating challenges for sustaining these less common species on the landscape (Tauer et al. 2012).

Silvicultural Systems

One of the unforeseen developments in silviculture has been the expansion in the range and scope of silvicultural systems. The last 30 years have seen management objectives expand to encompass a greater variety of economic, ecological, and social considerations. The development of silviculture during this period is evident in the zonation of forestry that was described by Tappeiner et al. (1986) and shortly thereafter by Salwasser (1990) and Seymour and Hunter (1992). As land management objectives diverged on different ownerships or within ownerships, the silviculture in these zones has also evolved and diverged. Many public lands have gone from emphasizing commodity production, or possibly emphasizing timber production in a multiple-use framework, to timber becoming a byproduct of management for other objectives (O'Hara et al. 1994). The application of silviculture in some forests, such as tribal ownerships, has actually increased over time in efforts to maintain culturally significant forest types and support local communities (Indian Forest Management Assessment Team for the Intertribal Timber Council 2013) whereas it has generally declined in many other ownerships. Many industrial ownerships have used technological advances in tree improvement, nursery stock development, fertilization, and other areas to intensify their efforts. Other lands fall in between these extremes.

One of the drivers of these changes includes the advent of forest certification systems that have made silviculture more environmentally conscious and, in other areas, led to major changes in management. For example, herbicide use, clearcutting, and adherence to BMPs, such as retention of mature trees in harvested areas, are more carefully scrutinized than before the emergence of certification in many regions. Another driver includes the expectation for real price increases in timber, for which, 30 years ago, the increase was approximately 4% (Oliver 1986); the reality has been lower, thereby discouraging some investment in silviculture, particularly practices such as precommercial thinning that may generate only long-term returns. The relatively sudden switch in industrial forestland ownership from integrated companies to REITs and TIMOs with the short time horizons described earlier has further affected silvicultural investment in private ownerships.

As anticipated 30 years ago, significant advances in the technology of plantation management have increased productivity and shortened rotations in areas where intensive silviculture is common. Continued improvement in the process of producing and outplanting seedlings has not only increased production but also changed the need for herbicide treatments. Tree improvement programs have developed faster growing trees, which have reduced rotation lengths and the effects of adjacency constraints that are part of some state forest practice rules. Herbicides are more effective and site-specific nutrient management is common in some regions such as the South (Jokela et al. 2010). Density management, sometimes in conjunction with pruning, has resulted in intensive management regimes where planting densities, thinning regimes, and harvest treatments can be planned with great precision to maximize production in highly predictable ways. These regimes have adopted the name of "precision forestry" (Dyck 2003).

Establishment and intermediate operations on other ownerships are also evolving. Lower planting densities and density management regimes that are more controlled are more common in managed forests. Likewise, precommercial and commercial thinning treatments are also more common. Alternatively, as was true 30 years ago, many stands are overstocked and in great need of thinning. These overstocked stands often comprise a backlog of stands needing treatment and represent a significant, if not overwhelming, accumulation of fuels in many western forests. Developing biofuel markets may provide one possible means for addressing these concerns in some regions (Evans and Finkral 2009).

Disturbance emulation to guide silviculture is a concept that has emerged in the last 30 years (Franklin et al. 2002, Seymour et al. 2006). On public lands, silviculturists have increasingly looked at natural processes, particularly disturbances, to guide sil-

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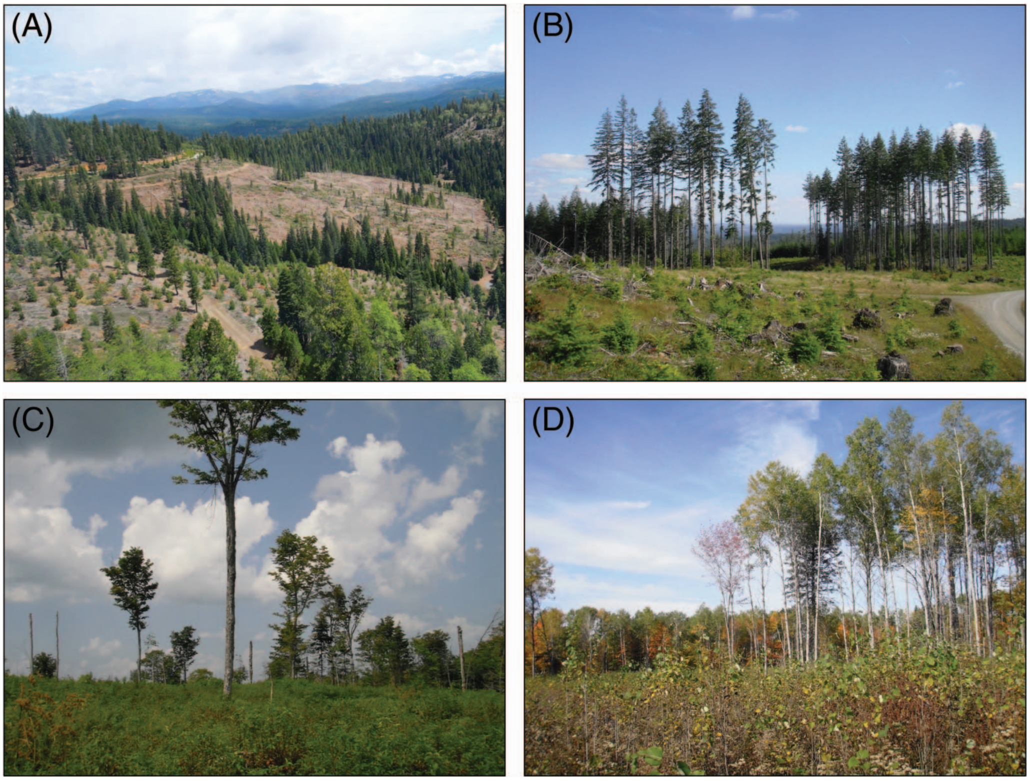

Figure 3. Variable retention after clearcut harvests in (A) mixed conifer forests in the Sierra Nevada Mountains, California, (B) Douglas-fir (*Pseudotsuga menziesii*) forests in western Washington, (C) northern hardwood forests in northeastern Vermont, and (D) aspen (*Populus tremuloides*) mixed wood forests in northeastern Minnesota.

viculture. Fire has generally become recognized as a natural part of virtually all forest ecosystems in the United States. However, fire emulation is limited for uses such as site preparation, fuel treatments, or understory vegetation control because of overriding concerns with smoke, fire control, liability issues, and potential losses to investment-laden stands. Therefore, fire emulation is increasingly common using mechanical surrogates for fire (North et al. 2012).

Another trend is the use of more uneven-aged or multiaged systems that attempt to emulate the effect of partial disturbance regimes. Clearcutting was an issue 30 years ago and still remains controversial today. Although there was a strong perception that even-aged stands resulting from stand replacement disturbances 30 years ago were common (Oliver 1986), today there is a growing realization that partial disturbances that leave multiple age classes are also common. Hence, an emerging trend is the management of stands with greater complexity and multiple age classes (O'Hara 2014), including places where even-aged stands may have been common. One example is the use of variable retention systems (Mitchell and Beese 2002) in the West and other regions as an alternative to clearcutting (Figure 3). These systems generally leave multiaged stands of two age classes that are seemingly in response to public concerns rather than disturbance emulation. Whereas disturbance emulation is a common feature of contemporary ecological-based silviculture, actual implementation of disturbance emulation is limited by the realities of modern society, particularly in fire-dependent ecosystems. In addition, even-aged management based on clearcutting remains a dominant approach on many lands, including private lands in the Southeast and Pacific Northwest where intensive plantation silviculture predominates.

Modern forestry is also concerned with the effects of disturbances when disturbance regimes are changing. Accumulations of fuels and, possibly, climate change are leading to large megafires, the extent and intensity of which are often outside historic norms (Adams 2013). Insects and pathogens—both native and non-native—are also increasing threats to forest management and are often exacerbated by climate change. Indeed, the presences of many invasive threats in some forests, such as in the Northeast, threaten these systems with wholesale changes in species composition and corresponding changes in ecosystem function, resulting in an increasing emphasis on silvicultural systems that create mixed species and multiaged conditions to spread risk (Figure 4; Waring and O'Hara 2005).

Silviculture often has few options in these situations. Silviculture can be effective for reducing fuels and fire threats. However, excessive fuel accumulations on extensive areas in western forests represent a virtually insurmountable problem as these fuels accumulate faster than they are treated. Treatments of native and invasive insects and pathogens are also limited by few management options and problems that occur at scales that make treatment regimes infeasible. A common strategy is to manage to increase resistance or resilience of forest ecosystems to these threats and the more general threat of a changing climate. This is a wide-ranging strategy, similar to a coarse filter approach (sensu Hunter 1990), to direct forest development in response to a broad suite of threats rather than a specific one.

Flexibility is becoming a common attribute to silvicultural planning and implementation on many public lands. Rather

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Figure 4. Examples of silvicultural systems for addressing current and future threats and uncertainties related to invasive insects and changing disturbance regimes and climate conditions. (A) Management for multiaged, mixed-species forest conditions in the Sierra Nevada Mountains, California to increase resistance and resilience to future disturbances. (B) Offsite direct seeding of red oak (*Quercus rubra*) in northern hardwood forest in northeastern Vermont and (C) off-site planting of ponderosa pine (Willamette Valley variety; *Pinus ponderosa var. willamettensis*) in young Douglas-fir plantation in western Washington to increase representation of drought-resistant species. (D) Group selection harvest in black ash (*Fraxinus nigra*) swamp in north-central Minnesota that has been planted with several non-ash species to reduce vulnerability of site to the introduced emerald ash borer (*A. planipennis*).

than standard guides for widespread implementation, managers are given more flexibility to design treatments to encompass stand-level objectives or variations in site and structural characteristics of individual stands. This trend reinforces a traditional value of silviculture that it is site specific and focused on existing stand structural features and site conditions.

This flexibility is important to strategies to increase forest complexity. Recent decades have often simplified stand structures, resulting in simple landscape patterns. A more varied set of silvicultural options will help create more variability at multiple scales. Variable-density thinning (VDT; Carey 2003) is an example of a treatment that represents part of a contemporary silviculture makeover in the last 30 years. VDT attempts to increase heterogeneity by essentially thinning in greatly different ways within a single stand. Although this increases stand-level heterogeneity, it also requires a rethinking of the traditional concept of the stand (O'Hara and Nagel 2013).

Although restoration strategies are increasingly common on public lands, there is an increasing recognition that directing stand development to conditions of the past, often using a historical range of variation as a target, is not as important as preparing stands for future conditions (Millar et al. 2007, O'Hara 2014 p 177). Hence, restoration is evolving to recognize the value of understanding past conditions in the design of future targets if possible, but with a greater emphasis on future goals.

The silvicultural systems of today are generally more complex than anticipated 30 years ago. The technology of plantation forestry has advanced, and the range of structures for management on many other lands has greatly expanded to include numerous variations on mixed-species or multiaged stands. As a result, the demands for silviculture and the demands on silviculturists have never been greater.

Conclusion

Each period in the history of forest management in North America has witnessed great changes in both forest conditions and the factors that influence their management. Reflecting on the changes in ownerships, objectives, technology, and threats that have occurred over the past 30 years, it is hard to imagine another period over which the factors influencing the practice of silviculture have shifted with such magnitude and rapidity. Although economics was a primary emphasis of silvicultural activities three decades ago, there has been an increasing emphasis on ecological and noneconomic social values from forests, particularly on public lands. This emphasis reflects both changes in federal and state-level policies as well as public expectations from managed forestlands, including sustained delivery of nonconsumptive ecosystem services such as carbon sequestration and water filtration (Duan et al. 2016). Likewise, addressing the increasing number of threats to forests in the form of invasive plants, insects, and diseases and alterations to natural disturbance regimes has evolved into a central objective of many silvicultural systems as managers increasingly confront novel ecosystem conditions. These changes and chal-

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lenges have all occurred within the context of declining funding for fundamental silviculture research and declining markets for forest products; this will hamper our ability in the next 30 years to make the great gains in silvicultural practice observed over the past 30 years. This will also almost certainly limit our ability to address the ever-growing suite of challenges facing sustainable forest management.

It is likely that the next 30 years will continue to include greater emphasis on silvicultural systems that integrate provisions for ecological objectives and that address and minimize the impacts of invasive species and changes in environmental conditions and disturbances associated with climate change (Figure 4; D'Amato et al. 2011, Malmsheimer et al. 2008). These systems and others focused on postdisturbance recovery will become particularly important in the West, where the prevalence of overstocked conditions and associated megafires and severe insect outbreaks will likely worsen over the next 30 years as the low levels of management in these areas continue to be outpaced by these changing conditions. As with the past 30 years, there are likely many unforeseen changes that will manifest over the next few decades affecting the ways in which silviculture in the United States is practiced; however, we hope that the current emphasis on adaptive approaches and technology to inform decision-making will provide a framework to deftly address the challenges and opportunities that the next 30 years of forest management will bring.

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