REVIEW

Research Strategies for Increasing Productivity of Intensively Managed Forest Plantations

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ABSTRACT

Intensive management practices increase productivity of forest plantations by reducing site, stand, and biological limitations to dry matter production and by maximizing the allocation of production to harvestable tree components. The resulting increase allows greater fiber production from a smaller land base and provides market incentives to keep these lands under forest use. The Southeast and Pacific Northwest contain the largest area of intensively managed plantations in the United States, with smaller pockets in the Midwest and other regions. Projected increases in US planted forest area are among the highest of any world region but maximum tree growth rates and returns on forestry investments are lower than those in South America. Addressing four critical information needs may help ensure that planted forests remain a competitive timber resource and sustainable land use in the United States: (1) improved capacity for understanding and predicting responses to intensive management; (2) technology for sustaining productivity, particularly under intensive biomass harvest; (3) expansion of silvicultural research networks to examine responses across a variety of sites; and (4) improved technology transfer to a broader range of landowners.

Keywords: fiber production, plantation forestry, intensive silviculture, biomass

Traditional and emerging markets for wood products and bioenergy are likely to increase pressure on forests and create incentives for enhancing their productivity through intensive management. Intensive management relies on manipulation of site resources, tree genetics, and stand structure to optimize tree growth and is most common on industrial forestland. Intensive practices are most successful when they strike the proper balance between mitigating limitations on productivity, maximizing allocation of production to harvestable tree components, providing a positive economic return on investments, and maintaining or enhancing site productivity and environmental quality.

From a broad regional perspective, enhanced productivity on the portions of forested landscapes devoted to sustainable fiber production allows greater flexibility for management of the remaining land base (Gladstone and Ledig 1990, Sedjo and Botkin 1997). In addition, forests that are productive and that yield positive net revenues provide market incentives against conversion to other land uses that offer little or no conservation value. Purchasers of fiber, driven by the public at large, also increasingly demand that forests are sustainably managed and that environmental values are protected. These demands are prompting formal adoption of best management practices (BMPs), certification systems, and other guidelines designed to protect water quality, soil productivity, and wildlife habitat. Research has confirmed the effectiveness of BMPs in protecting water quality (Aust and Blinn 2004, Ice 2004, Vowell and Frydenborg 2004), with implementation rates most often above 80 or 90% (Southern Group of State Foresters 2008, Schilling

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2009) and estimated to average 89% nationally (Ice et al. in press).

Information is needed to successfully address the confluence of technological, biophysical, and environmental issues surrounding intensively managed forests. This overview describes current intensive plantation management practices in the United States and their role in increasing forest productivity. Although a number of plantation tree species could be considered intensively managed in these and other regions, we confine our analysis to predominately three species supported by genetic tree improvement programs. These species are the southern pines (primarily loblolly pine [*Pinus taeda* L.], Douglas-fir [*Pseudotsuga menziesii* {Mirb.}] Franco) in the Pacific Northwest, and the poplars (*Populus spp.*) in the Midwest. We suggest that information needed to achieve further boosts in productivity fall into two general categories: (1) scientific research to understand the functioning of biophysical systems, including their response to management practices, and (2) technology transfer to ensure application of the best information available by resource managers and landowners. Although not addressed in this analysis, it is also critical that financial returns from forestry investments be quantified and communicated to landowners to provide them with information and incentives they can use as a basis for deciding whether to implement intensive management practices.

Wood Production, Tree Growth Rates, and Forestry Investments

The area of forest plantations and their contribution to the production of wood products is increasing substantially on a global scale (Bael and Sedjo 2006), with wood production in any given region a function of available land and forest productivity. In one recent analysis, changes in global wood production from planted forests were projected from 2005 to 2030 based on three scenarios: (1) low rates of expansion in planted forest area with no increase in productivity; (2) expansion of planted forest area at current rates with no increase in productivity; and (3) expansion of planted forest area at current rates with increased productivity based on expected genetic, management, and technological improvements (Carle and Holmgren 2008). Planted forest area in North and Central America was projected to increase at a higher rate (43%) than any other continent, and 96% of this area was in the United States. However, wood production in North and Central America was estimated to increase only 26% as a result of technological improvements and associated increases in management intensity alone. This rate exceeds only Europe (11%) and falls substantially below the increase expected from management intensification in South America (46%) and Australia/New Zealand (47%). These comparisons underscore the need to confirm or refute the assumption of lower increases in productivity achievable from intensive management in the United States.

Technological advances from forest research are widely disseminated but only partly transferable among regions; thus, their impact and benefits are greatest for the forest types and sites where the research is conducted. Given current trends in global competition and ownership patterns in the United States, maintenance of forest products manufacturing infrastructure and associated timber markets may depend on regional adoption of intensive practices by a broader spectrum of landowners, making effective technology transfer critical.

Growth rates for intensively managed tree plantations in the United States compare favorably with those in most other world regions. Mean annual stemwood increment (MAI) for intensively managed loblolly pine, the most extensively planted tree species in the United States, commonly exceeds 5.6 dry tons $ac^{-1}\,yr^{-1}$ (350 $ft^3\,ac^{-1}\,yr^{-1}$; wood density from Birdsey 1992; Fox et al. 2007a), and can exceed 8.0 dry tons $ac^{-1}\,yr^{-1}$ (500 $ft^3\,ac^{-1}\,yr^{-1}$) on the best sites (Sampson and Allen 1999, Borders and Bailey 2001). These rates are comparable with values reported for primary plantation species in Southeast Asia, China, Europe, Australia/New Zealand, and South Africa, but are low compared with MAIs for *Eucalyptus spp.* in South America, which can reach almost 16 dry tons $ac^{-1}\,yr^{-1}$ (1,000 $ft^3\,ac^{-1}\,yr^{-1}$; wood density from Brown 1997; Del Lungo et al. 2006).

More even seasonal distribution of precipitation, narrower temperature fluctuation, longer growing seasons, and a lack of pests were cited as factors responsible for higher growth rates of loblolly pine in Hawaii than in its native Southeast; however, growth rates of loblolly pine under intensive management (in this case, with fertigation) were similar in both locations when stands were kept below carrying capacity to limit potential mortality (Harms et al. 2000, Samuelson et al. 2008). The other primary plantation species in the United States, Douglas-fir, has maximum growth rates similar to loblolly pine, with periodic annual increment (PAI) and MAIs reaching 7.4 and 4.4 dry tons $ac^{-1}\,yr^{-1}$ (500 and 300 $ft^3\,ac^{-1}\,yr^{-1}$), respectively, for managed plantations in western Oregon and Washington (specific gravity from Birdsey 1992, Curtis et al. 1997, Marshall and Curtis 2002). This PAI is lower than that attainable by Douglas-fir from Pacific Northwest seed sources growing in New Zealand and other sites in the Southern Hemisphere, where growth reaches 10.4 dry tons $ac^{-1}\,yr^{-1}$ (700 $ft^3\,ac^{-1}\,yr^{-1}$) (Waring et al. 2008). Although mean annual precipitation and temperature are similar for these different regions, model-based growth analysis suggests that higher temperature extremes, lower growing season precipitation, and higher vapor pressure deficits reduce stomatal conductance and total photosynthesis in the Pacific Northwest (Waring et al. 2008).

The economic performance of intensive plantation management depends on factors used in conventional financial analysis (Klemperer 1996) and on the response of these factors to global trends in supply and demand (Oliver and Mesznik 2005). Cubbage et al. (2007) noted that higher internal rates of return for forestry investments in South America were attributable to growth rates of exotic plantations that doubled or tripled those of plantations in the US Southeast. Despite similar plantation establishment costs, returns ranged from 13 to 23% for eucalyptus plantations and 9 to 17% for loblolly pine in South America, in contrast to just over 9% for loblolly pine in the southeastern United States. However, they concluded that more intensive management coupled with lower investment risks could make forestry investments in the United States equally attractive to South America (Cubbage et al. 2007). Increasing management intensity increases the cost of stand establishment and management but can also reduce costs per unit of wood if growth and value responses are sufficient (Allen et al. 2005).

Return on investments in forest productivity research itself is more difficult to quantify because it involves not only the cost of the treatments being explored and potential growth responses, but also the cost and efficiency of the research activity that yields the information. A compilation of results from research investment studies claimed the highest economic rates of return for research on forest pest management (60–86%) and containerized seedlings (37–111%), lower rates of return for research on operational efficiency of timber harvest (17%) and forest nutrition (9–12%), and low average return (only 0–7%) for southeastern softwood research in aggregate (National Research Council [NRC] 2002). In the same analysis, tree improvement research had a higher benefit/cost ratio (34) than research on growth and yield modeling and herbaceous weed control (17–21% and 16%, respectively). Economic returns for research on biotechnology and other intensive practices were acknowledged as potentially substantial but too poorly documented to establish with a reasonable degree of accuracy. Because of the number of variables involved, such cost/benefit figures have a wide margin of error but could serve as a starting point for more specific assessments under defined conditions.

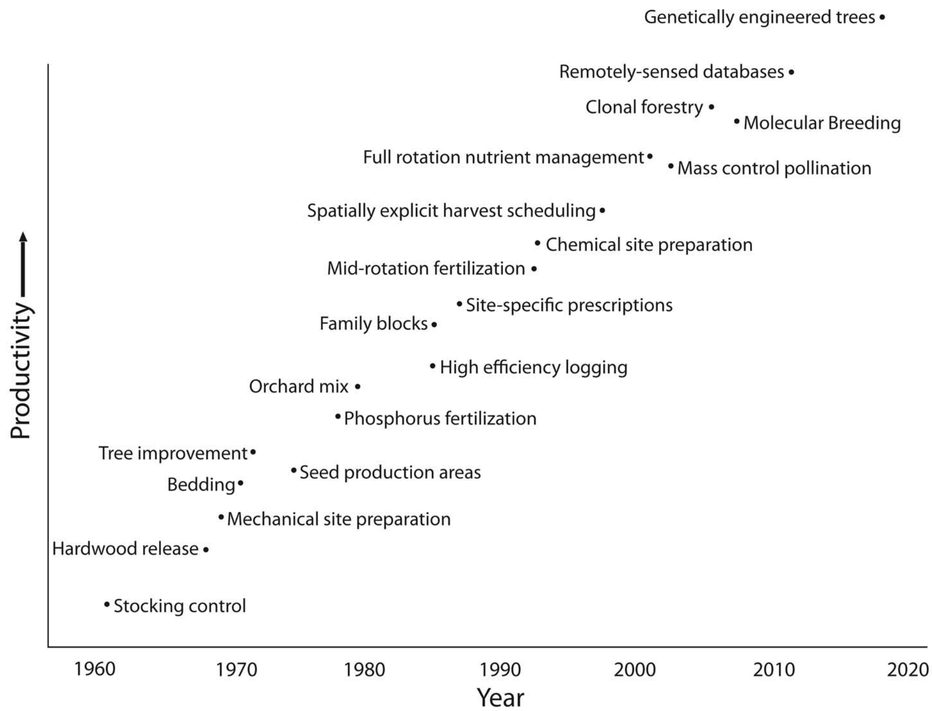

Figure 1. Timeline illustrating forest management and technology advancements from 1960 to 2020. Practices and dates of implementation vary across regions. (Derived from a figure originally developed by P.M. Dougherty, ArborGen, LLC.)

Intensive Management in the United States

The Southeast and Pacific Northwest have the most productive forests and generate more harvestable wood than other US regions. It is therefore not surprising that forests in these regions are managed most intensively. The Southeast, with an estimated 32 million ac of pine plantation (Wear and Greis 2002), contains the largest area of planted forests, with the Pacific Northwest coming in second with about 13.6 million ac of plantations (Stanturf and Zhang 2003). Although there are considerable areas of managed forests in the Midwest, Rocky Mountain, and Northeast regions, only a small proportion could be considered intensively managed plantation forests.

Southeast

Extent and Benefits of Intensive Management

Almost all intensive management in the Southeast is associated with loblolly and slash pine (*Pinus elliottii* Engelm.) plantations (Fox et al. 2007a). Plantation management practices commonly include control of competing vegetation with herbicides, management of tree nutrition through addition of fertilizers, thinning, and maximizing growth potential with genetically improved growing stock. Site preparation practices at stand establishment may include bedding, subsoiling, and the use of fertilizer and herbicides to increase early root growth and reduce herbaceous and woody competition (Edwards et al. 2006). On an annual basis, roughly 1 million ac of southern pine receive herbicide for site preparation; 664,000 ac for release (first growing season, hardwoods, and shrubs); and 700,000 ac for herbaceous weed control (just after planting; McCullough et al. 2005). The area of fertilized pine plantations roughly doubled every 2 years between 1991 and 1999, but declined to about 1.2 million ac by 2005 because of changing market conditions and increasing fertilizer costs (Albaugh et al. 2007).

Implementation of plantation management technologies (Figure 1) have increased per acre operational pine yields by up to six times those of naturally regenerated second-growth stands (Carter and Foster 2006). Of the total increase in productivity relative to unimproved plantations, 35% has been attributed to nutrition, 35% to vegetation management, 20% to tree improvement, and 10% to a better match between silviculture and soil-site classification (Stanturf et al. 2003).

Almost all 1.2 billion loblolly pine and 150 million slash pine seedlings planted each year originate from tree improvement programs, and seedlings from third-generation tree improvement programs are now available (McKeand and Allen 2005). Estimated volume gains from second-generation versus first-generation seed orchards range from 13% in the Atlantic Coastal Plain to 21% in the Piedmont, while volume gains from seed mixes with only the best open-pollinated families may reach 35% (Li et al. 1999, McKeand et al. 2006a). One assessment of 450 clones at two sites showed volume growth for the best clones after 4 years was more than 50% higher than for seedlings from an unimproved seedlot (Isik et al. 2005). Although tree breeding programs have traditionally emphasized increased volume growth, disease resistance, and stem form, wood quality characteristics such as stiffness and density are now often included in progeny tests and selection of families (Isik and Li 2003, Byrum et al. 2005, Li et al. 2007, Roth et al. 2007b). Consideration of wood quality will likely expand at a greater rate in the future as economic incentives for specific wood traits develop in response to specialized markets for bioenergy and biomaterials.

Factors Limiting Productivity

As with other forest types, productivity of southern pine is limited by site resources and the ability of trees and stands to acquire and use those resources. Based on replicated studies across the Southeast, soil nutrient availability rather than site water balance has been identified as the primary site factor affecting loblolly pine productivity, in part because nutrient availability influences maximum stand density to a greater extent than genetic and climatic factors (Jokela et al. 2004). Even on a very dry, sandy site, a fertilization-irrigation study in North Carolina showed that nutrients were more limiting to productivity than water (Albaugh et al. 2004). Water stress limits loblolly pine productivity near the western edge of its range, however, and stand density management may assume greater importance in that subregion (Hennessey et al. 2004). Geographic and physiographic factors have been found to be primary drivers of stand growth under both high and low intensity management (Amateis et al. 2006).

Experiments in Georgia and North Carolina that provided near-optimal resources through complete competition control and annual fertilization or fertigation resulted in stem PAIs ranging from 5 to 12 dry tons ac^{-1} yr^{-1} (314 to 755 ft^3 ac^{-1} yr^{-1}), with MAIs of about one-half of those values (Albaugh et al. 2004, Borders et al. 2004, Samuelson et al. 2008). Phosphorus fertilization alone during stand establishment on P-deficient southeastern Coastal Plain soils can sustain growth responses up to 0.8 dry tons ac^{-1} yr^{-1} (50 ft^3 ac^{-1} yr^{-1}), and N + P fertilization at crown closure can increase growth by a similar amount over 8–10 years across a wide range of sites (Fox et al. 2007b). Competition control is a practice that influences both nutrient and water availability to the primary tree crop. One study of hardwood competition over two decades found stand volumes increased with hardwood control in 13 of 14 field trials, with gains inversely related to site quality and typically about 870 ft^3 ac^{-1} by 20 years of age (South and Miller 2007).

Tree improvement programs have had a substantial influence on southern pine productivity by altering tree characteristics such as leaf area (total light capture) and growth efficiency (stemwood production per unit leaf area). Although the greatest returns come from planting improved seedlings on the most productive sites (McKeand et al. 2006a), improved genotypes are more productive than poorer genotypes regardless of site quality (McKeand et al. 2006b). The best pine families also generally respond most positively to intensive management practices (Roth et al. 2007a). The application of new biotechnological approaches for enhancing forest productivity and controlling individual tree characteristics will play an integral role in tree improvement programs and across the full spectrum of management intensities (Whetten and Kellison 2010).

Pacific Northwest

Extent and Benefits of Intensive Management

Intensive management in the Pacific Northwest has focused predominantly on Douglas-fir because of its growth potential, yield, and economic value. Other intensively managed species include red alder (*Alnus rubra* Bong.), ponderosa pine (*Pinus ponderosa* Laws.), and western hemlock (*Tsuga herterophylla* [Raf.] Sarg.). Red alder log prices have recently been comparable with those of Douglas-fir, and ongoing silvicultural field trials are yielding useful information for managing red alder plantations (e.g., Hibbs et al. 2007). Ponderosa pine plantations are common east of the Cascade Range and in the Klamath-Siskiyou province of southwestern Oregon and northern California, although plantation management is practiced most intensively on large private ownerships in southwestern Oregon and northern California. Where site conditions dictate, western hemlock is planted and intensively managed instead of or in mixture with Douglas-fir, but wood strength and product value render Douglas-fir the preferred species where both can be grown. Douglas-fir stands classified as seedling/sapling, pole, or small sawtimber cover about 7.3 million ac of nonfederal timberland in Oregon and Washington (Azuma et al. 2004, Gray et al. 2005). Western hemlock and red alder stands of the same size class cover about 1.5 and 1.8 million ac, respectively.

Productivity gains from management intensification are partly reflected in the historical progression of regional growth and yield estimates in Douglas-fir. For many years the standard for estimating Douglas-fir growth and yield potential was "Bulletin 201," first published in 1930 and revised in 1949 and 1961 (McArdle and Meyer 1930, McArdle et al. 1961). The initial normal yield tables provided an estimate of net growth under no management and full stocking, but revisions expanded the scope to stands of less than full stocking. On the most productive sites, PAI of Douglas-fir stemwood averaged almost 4.4 dry tons ac^{-1} yr^{-1} (300 ft^3 ac^{-1} yr^{-1}) in the youngest stands sampled (total age of approximately 20 years), with MAIs peaking at approximately 3.1 dry tons ac^{-1} yr^{-1} (210 ft^3 ac^{-1} yr^{-1}) by age 60–70 years. Recognizing that intensive management would capture much of the mortality not accounted for in normal yield tables, Staebler (1955) estimated that gross PAI and MAI on the best sites could reach 5.1 dry tons ac^{-1} yr^{-1} (345 ft^3 ac^{-1} yr^{-1}) and 4.0 dry tons ac^{-1} yr^{-1} (270 ft^3 ac^{-1} yr^{-1}), respectively. The implied yield gain from this increase in management intensity was 0.9 dry tons ac^{-1} yr^{-1} (60 ft^3 ac^{-1} yr^{-1}), or 29%. Long-term silvicultural trials (e.g., Curtis et al. 1997) have now documented MAIs as high as 4.4 dry tons ac^{-1} yr^{-1} (300 ft^3 ac^{-1} yr^{-1}), suggesting a 43% increase on at least some sites.

Intensive Douglas-fir plantation management as currently implemented includes genetic tree improvement, chemical site preparation, release from competing vegetation, fertilization, and stocking control (initial spacing and thinning). Virtually all Douglas-fir seedlings operationally planted today are grown from improved seed produced in wind-pollinated seed orchards (Howe et al. 2006). Second-generation breeding and testing of Douglas-fir is underway in many subregional tree improvement cooperatives, with expected gains in volume yield up to 50% at age 15 years (Jayawickrama 2006). However, realizable gains for Douglas-fir at or near rotation age (45–70 years) are largely unknown because of the relatively young age of first-generation (30 years) and second-generation (5 years) progeny tests, a lack of data on stand-level performance of operationally deployed family mixes (St. Clair et al. 2004), and the uncertain longevity of early growth advantages (Gould et al. 2008).

Competing vegetation is routinely controlled in Douglas-fir plantations by chemical site preparation and/or 1st-year release, with some sites requiring a 2nd-year release. These intensive treatments are often required to ensure adequate or desired seedling survival rates, but they also consistently enhance early growth rate of planted seedlings (Rose and Rosner 2005, Rose et al. 2006, Rosner and Rose 2006). Cumulative seedling growth response can reach 350% during the first 10 years after release (Rose et al. 2006). Early time gain for achieving a given yield varies by regime and time since last release (Maguire et al. 2009), and both time gain and yield gain (increase in yield for a fixed rotation) probably vary considerably among site types (Wagner et al. 2006). Because Douglas-fir rotation ages are relatively long (45–70 years), estimates of long-term growth effects must still be confirmed by maintaining competing vegetation trials closer to rotation age (e.g., Newton and Cole 2008, Harrington and Tappeiner 2009).

Nitrogen fertilization of Douglas-fir plantations has been a common practice in the Pacific Northwest for several decades, with a standard application rate of 200 lb N ac^{-1} as urea. Average stemwood growth response has been estimated at 0.4–1.3 dry tons ac^{-1} yr^{-1} (30–90 ft^3 ac^{-1} yr^{-1}) for a 6-year period after application, with greatest responses on low to medium sites with moderate stand density (Heath and Chappell 1989). Direct growth responses seem to last 4–5 years (Brix 1983) and indirect responses last 8–12 years after fertilization (Stegemoeller and Chappell 1991).

Factors Limiting Productivity

Few nutrient limitations beyond those of nitrogen have been identified for Douglas-fir (Walker and Gessel 1991, Mainwaring and Maguire 2008); as a result, nitrogen fertilization will continue to dominate as the most common nutrient amendment. Competing vegetation control probably increases availability of both soil moisture and nutrients (Rose and Ketchum 2003), but these effects are difficult to separate in many regions (Nambiar and Sands 1993). Field trials have shown large differences in soil water availability and xylem water potential among Douglas-fir seedlings experiencing different levels of competing vegetation (Dinger and Rose 2009). Low soil water availability and high vapor pressure deficits resulting from prolonged summer drought probably represent the dominant limitation to Douglas-fir productivity in its natural range (Waring et al. 2008).

Although fertilization and other intensive management practices such as competition control and genetic tree improvement have substantially increased productivity of Douglas-fir across much of the Pacific Northwest, inherent site quality remains a critical factor affecting yields. Some of the highest growth rates reported for the region occur in stands located on high-quality sites with no intensive practices other than frequent thinning to regulate stand density.

Midwest

Extent and Benefits of Intensive Management

The Midwest has a rich history of intensive management to improve plantation productivity for fiber and other outputs. Research and development of conifer species dominated tree improvement programs in the region until the Arab oil embargo of the 1970s (Dickmann 2006). The embargo prompted extensive evaluation of intensive forest management practices to increase productivity of short-rotation woody crops (SRWC). Given their established use in other parts of North America and the world (Dickmann 2001), along with broad genetic variation and high productivity (Rajora and Zsuffa 1990, Zalesny et al. 2009), *Populus* species and hybrids (i.e., poplars) were selected as the SRWC of choice in the Midwest (Dickmann 2006). Breeding of poplars in the Midwest began in the 1950s and continues today with four species commonly used as parents in intra- and interspecific crosses: *Populus deltoides* (eastern cottonwood), *Populus trichocarpa* (western black cottonwood), *Populus nigra* (European black poplar), and *Populus maximowiczii* (Japanese poplar). To increase selection gains relative to traditional commercial clones, poplar breeders throughout the region have prioritized productivity as well as traits such as pest and disease resistance (Coyle et al. 2005) and rooting ability (Zalesny et al. 2005).

Currently, almost all intensive management in the region is associated with poplars, with *Salix* species and hybrids (i.e., willows) being tested in experimental plots but not deployed commercially. Intensive management practices used to establish and grow poplar include site preparation (i.e., disking, tilling, spraying preemergent herbicide, to name a few) followed by planting favorable genotypes as rooted (southern part of region) or nonrooted (northern part) stock. Stand management consists of intensive field cultivation and application of fertilizer, herbicide, and/or insecticide (Stanturf et al. 2001). Similar to southern pine plantations, some of these applications have declined in recent years because of changing market conditions and increasing production costs.

Intensive management and genetic improvement of poplars offer great potential for optimizing tree growth and productivity, especially in southern parts of the region where potential conifer plantations and native aspen are not widely distributed. In northern states such as Wisconsin, Minnesota, and Michigan, productivity of intensively managed poplar can be up to eight times greater than native aspen (Netzer et al. 2002, Zalesny et al. 2009). Mean annual aboveground increment of 4 dry tons ac^{-1} yr^{-1} is common, with advanced genotypes exhibiting nearly 2.5 times as much growth. Reported poplar biomass productivity in the Midwest is highly variable, however, with PAI ranging from 2 to 10 dry tons ac^{-1} yr^{-1} (Netzer et al. 2002, Goerndt and Mize 2008, Zalesny et al. 2009). In addition to productivity increases, advancements in tree improvement and plantation management technologies provide opportunities for substantial scale-up of commercial plantation area, which is currently about 25,000 ac centered in Minnesota. Expanding the area of highly productive poplar plantations may be particularly vital given the predicted shortage of aspen supply within 10–20 years because of a lack of suitable stumpage within harvestable diameter classes (Piva 2007, Domke et al. 2008).

Factors Limiting Productivity

Poplar productivity is limited by the inherent potential of the specific genotypes deployed, soil and climatic conditions, and, most importantly, genotypic responses to varying environmental conditions across the region. Site conditions are particularly important in the northern part of the region, where soils contain greater amounts of sand and gravel and have inherently lower fertility and water holding capacity. Precipitation typically increases from north to south in the region and moisture can be a major limiting factor. As a result of extensive poplar tree improvement efforts, selected genotypes have exhibited much greater vigor and productivity than traditional clones across a range of site conditions (Zalesny et al. 2009). Such genotypes have been developed to capitalize on heterosis, with hybrids exhibiting greater productivity than either parent (Scarascia-Mugnozza et al. 1997).

From a genecology perspective, movements of poplar genotypes beyond their zones of adaptability can greatly limit productivity and influence other traits such as pest/disease resistance, rooting ability, and physiological processes (Farmer 1996). Intensively managed clones have been categorized into two groups, depending on whether genotypes exhibit favorable growth: (1) across the region (i.e., generalists) or (2) at specific sites (i.e., specialists; Zalesny et al. 2005, 2009). Overall, failure to consider interactions between tree genetics and site conditions (i.e., G × E) can have substantial impacts on plantation success, both from the standpoint of limiting productivity of favorable clones established at mismatched sites and of gaining productivity from otherwise recalcitrant clones when grown under optimal site conditions (for those clones).

Research and Information Needs

Understanding and Projecting Forest Responses to Intensive Management

Understanding processes controlling tree growth is critical for predicting stand responses to environmental conditions and silvicultural practices, particularly if the conditions or practices of interest exceed the range currently covered by historic and ongoing field trials. Based on one evaluation of long-term loblolly pine plantation field trials in Southeast loblolly pine plantations, the following topics were identified as top priorities for research (Jokela et al. 2004): (1) demand, uptake, utilization, and cycling of nutrients across and within stands; (2) mechanisms of intraspecific tree competition and the role of thinning in regulating this competition; and (3) soil, climate, and ecophysiological constraints on the growth potential of fixed genotypes.

Models that incorporate basic physiological processes have been suggested as one promising approach for addressing the complex of factors impacting tree function and site resource availability (Jokela et al. 2004). This mechanistic approach requires collection of unconventional stand and site attributes (e.g., water holding capacity, leaf area index, soil and foliar nutrient content) that are coupled with soil-landform databases compiled from remote sensing and other technologies. Substantial progress has been made in developing techniques to diagnose nutrient limitations, but more work is needed to improve their consistency across a range of sites (Gregoire and Fisher 2004, Fox et al. 2007a). Another approach is to link tree morphological and physiological traits that can be measured during progeny testing to functional performance in terms of growth, stem form, wood quality, and pest resistance (Nelson and Johnsen 2008). Toward this end, incorporating ecophysiological parameters such as belowground carbon allocation and morphological traits such as frequency of mycorrhizal root tips into conventional tree improvement programs is a critical need (Martin et al. 2005). An entirely different set of traits may be required to assess the suitability of families and genotypes for producing wood that is optimal for bioenergy and other specialty markets.

Major information needs identified for intensive plantation silviculture in the Pacific Northwest are similar to those identified for other regions. High priorities include (1) site characterization with respect to soils and climate, (2) identification of key mechanisms driving growth and productivity, (3) development of growth models that functionally integrate site characteristics and growth mechanisms, (4) representation of genetic improvement through physiological and morphological parameters in growth models, and (5) quantification of links between tree growth or tree morphology and three-dimensional characterization of stemwood (to facilitate assessment of wood quality for various end uses).

Topography, soils, and climate are extremely variable in the Pacific Northwest, so many of the limitations to site productivity and the corresponding responses to silvicultural activities are site specific. Management efficiency should therefore be improved if regional average responses can be replaced by more site-specific prescriptions. Successful implementation will require a site characterization protocol that is cost-effective, focused on attributes linked to mechanisms represented in corresponding growth models, and easily performed in a repeatable manner by different resource managers.

Research gaps for enhancing productivity of SRWCs in the Midwest, likewise, do not deviate dramatically from those identified for the Southeast or Pacific Northwest. Research conducted over the last few decades has defined key elements of poplar production systems in the region. However, additional basic and applied research is vital for producing feedstocks for fiber, wood products, and energy while practicing ecological sustainability. From a plantation productivity perspective, understanding limitations to feedstock production rate is the major information need. Plantation systems for fiber, wood, and energy in the Midwest must integrate and optimize biological, ecological, and economic factors across the landscape. Within this integrated approach, poplar breeding programs in the Midwest and other regions are working toward commercializing genotypes that (Stettler et al. 1996) (1) exhibit high levels of productivity and harvestable biomass (Goerndt and Mize 2008, Zalesny et al. 2009); (2) produce sufficient root systems to ensure successful establishment (Zalesny et al. 2005); (3) remediate and stabilize soils, sediments, and water (Schultz et al. 2004, Zalesny et al. 2007); (4) tolerate or resist pest and pathogen attacks (Newcombe et al. 2001, Coyle et al. 2005); and (5) allocate resources to leaf and branch material to sustain physiological processes necessary for increased productivity (Scarascia-Mugnozza et al. 1999, Dickmann 2001).

Sustaining Forest Productivity

Intensive plantation management often requires greater and more frequent removals of forest biomass than do more traditional management regimes. The emergence of markets and policies linked to forest-derived biomass energy have prompted renewed interest in the potential impacts of increased nutrient and organic matter removals and associated soil disturbance on long-term site productivity, sustainability, and environmental quality. This concern has led to the development of biomass harvesting guidelines in Minnesota, Missouri, Pennsylvania, and Wisconsin that in some cases restrict whole-tree harvesting and residue removal on sites deemed sensitive. Scientific support for such provisions is based more on conceptual understanding (e.g., residues provide organic matter and nutrients that sustain productivity) than on empirical, quantifiable relationships among residues, removals, inputs, and net productivity across a range of sites. Although intensive management may have greater potential for adversely impacting site productivity than do more traditional regimes, managers implementing intensive practices typically have more resources and technologies to identify, prevent, and mitigate negative effects.

One approach for assessing the effects of biomass removal on site productivity is to experimentally manipulate site resources. The US Forest Service Long-Term Soil Productivity (LTSP) network includes experimental biomass removals ranging from bole only to total aboveground biomass (whole trees and forest floor) combined with a range in soil compaction. Results, to date, suggest that most sites are remarkably resilient to these manipulations (Powers et al. 2005), even those that are extreme relative to operational practices. Related experiments, such as the Fall River Study in the Pacific Northwest (Ares et al. 2007) and the Cooperative Research in Sustainable Silviculture and Soil Productivity site network in the western Gulf Coastal Plain (Scott and Dean 2006), combine biomass removal and soil compaction with additional treatments typically applied in operational settings to ameliorate adverse impacts. In the latter study, whole-tree harvest substantially reduced pine biomass accumulation compared to stem-only harvest by age 7–10 years. However, fertilizer application fully reversed this effect, increasing tree growth in the whole-tree harvested plot by 47% relative to stem-only removals with no nutrients added. Many site productivity studies do not include amelioration practices such as fertilization to replace nutrients removed in harvested biomass. The presence or absence of competing vegetation has been shown to be more important than biomass removal in governing tree growth in many of the LTSP and associated studies (Powers et al. 2005, Sanchez et al. 2006, Ares et al. 2007). Although considerable work has been done to understand short-term effects of biomass removal on site productivity, long-term studies comprising repeated, intensive harvests are less common and represent a critical research gap.

Silviculture Site Networks

Networks of long-term silvicultural field trials such as those established by university–industry research cooperatives in recent decades have greatly advanced the understanding of forest responses to management practices and the mechanisms driving them. Long-term trials allow testing of specific hypotheses about mechanisms and magnitude of response to silvicultural treatment across a range of sites and can therefore serve as the basis for developing management prescriptions. Relevance of mission, activities, and output of forest research cooperatives is ensured by close and frequent communication with company and agency members. Member needs are communicated directly to research organizations, and results from funded projects flow directly back to practitioners. Recommendations are further modified after additional testing and feedback when member organizations apply the results operationally. Cooperative research incorporates the ultimate reality check for research efficacy because supporting members depend on the performance of silvicultural investments for their success. Extensive networks of field trials provide a critical foundation for predicting growth responses to management practices. These trials also provide valuable input data for both traditional models with a largely empirical base and "hybrid models" that combine empirical and ecophysiological approaches (Monserud 2003). For this reason, it is imperative not only to sustain field trial networks but also to expand their coverage to novel but strategically selected treatment combinations. Despite their successes, support for many research cooperatives has been declining due, in part, to shifts in institutional forest ownership away from integrated forest products companies to organizations with different objectives and time horizons, as described in the following section.

Transfer and Implementation of Intensive Management Research

Research on increasing and sustaining forest productivity is critical, but the technology that results from this effort must also be widely disseminated and applied to ensure that landowners maximize returns on investment and that society benefits from sustainable economic development, long-term fiber supply, and alternative energy production. Consistent with this view, the top research and development priority identified in the Forest Products Industry Roadmap (Agenda 2020 Technology Alliance 2006) was to "Update growth and yield models to account for changes in stand conditions, management practices, and environmental variables." Hybrid growth and yield models that incorporate key physiological processes may be the best approach for meeting this need, and relevant forest management guidelines and information sources must be integrated into such models to enable landowners to take fullest advantage of past research investments. Expanding the use of improved genetic stock may represent one of the most easily implemented facets of technology transfer that provides one of the greatest returns on landowner investment. Improved genetics not only increases volume growth with minimal cost but can also improve returns by enhancing stem quality and disease resistance (McKeand et al. 2006a).

Effective application of research results to field operations must recognize the wide diversity of forest owners and forestland managers and correspondingly wide range of financial resources, expertise, and information at their disposal. An important challenge is the transfer of information and research technology to nonindustrial private landowners who own 60% of forestland in the Southeast, 20% in the Pacific Northwest, and over 60% in the Midwest (Smith et al. 2009). Land-grant universities could expand their extension and outreach efforts to this important landowner group by promoting greater interaction among research cooperatives, small family forest landowners, forestry extension, and university outreach programs. Collaborating with and promoting the establishment of local forestry landowner associations could be particularly effective for transferring research technology to nonindustrial landowners. Although these landowners may have the flexibility to adopt new technologies and management systems, they are often limited by a lack of easily accessible information or financial resources. At the other end of the spectrum, dramatic changes in "industrial" or corporate ownership resulting from the acquisition of large contiguous forestland blocks by Timber Investment Management Organizations and Real Estate Investment Trusts are most likely impacting management objectives, time horizons, and consequent research needs. Given rapid and uncertain changes in forest ownership, management, and utilization, a challenge even greater than identifying and producing relevant and effective research and technology may be the development of an adaptable infrastructure to supply these needs.

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