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Sustaining Productivity of Planted Forests in the Gulf Coast Region

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Introduction

The forests of the Gulf Coastal Region provide the basis for its economic well-being. Because of the semitropical climate, abundant rainfall and availing topography, the nation's richest plant communities thrive. These forests are predominately privately owned. Millions of private landowners are committed to managing their forests for a broad array of values which include a sustainable wood supply, wildlife habitat, clean water and forest recreation such as hunting and fishing. The Region's forests are dynamic ecosystems, capable of supplying, over the long term with good stewardship, the myriad of products and services we have come to rely upon as the mainstay of the economy.

The Region's timberland consists of a diverse array of forest types, with much of the area covered by fast-growing pine types. Loblolly pine (*Pinus taeda L.)* is the most abundant species growing across the pine timberlands. It is the loblolly pine type that is the primary focus of the unprecedented demand on private lands to meet the needs of a wood-demanding public. This increasing burden on lands within the Region results from the national de-emphasis of timber management on public lands and the reclassification of much of our natural forests to a protected status.

There is increasing concern about the sustainability of these plantation forests because of the intensity of management and the potential change in climatic conditions. Sustainability has been defined as "managing resources productively in ways that are scientifically sound, ecologically enduring, socially desirable and culturally ethical" (Bawden 1989). There are divergent opinions as to what is "socially desirable" or "ecologically enduring." However, most would agree that maintaining forest productivity at relatively high levels indefinitely with no serious impairments of soil, water or biological components would qualify as sustainable (Burkett *et* al. 1996). There is the question of how to monitor the productivity of forests, particularly managed stands over long periods with repeated cropping.

In addition to the potential effects of more intensive forest management, shifts in climatic conditions may limit the productivity on many of the Region's soils. Hotter, drier summers would mean more regeneration failures, less growth, higher incidence of insect outbreaks, increased incidence and severity of fire, higher production costs, and restricted access for recreation and resource management (Southern Global Change Program [undated]). Increased winter rains would decrease growth on some sites (Shoulders and Tiarks 1980) and push up logging costs. Greater year-to-year variability in weather would make planning of forestry operations more difficult. However, climate change may pose more of a threat to natural forests than those actively managed (Office of Technology Assessment 1993), since a shift in climate would almost certainly exceed the ability of natural forests to migrate (Roberts 1989). With management, there are opportunities to mitigate climate changes by: 1) establishing an expanded forest seedbank program, 2) developing strategic plans for responding to major forest declines, 3) preparing a forest management response to Climate change, and 4) improving incentives for pri-

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vate management (Office of Technology Assessment 1993).

There is a real need to have the technology to monitor the productivity of forests over a long term, and to understand stand responses to, and environmental implications of silvicultural practices. Such information is critical to understanding if forests are being influenced by shifts in climate or are just responding to changes in management practices. Critical, also, is information that will allow forest managers to change silvicultural practices to mitigate the effects of climate change.

Productivity is usually determined by measuring the site's capacity to produce dry matter over time (Powers et al. 1990). Conventional forest management is focused upon tree boles, and most of what we know about forest productivity is based on simple measures of these boles. Half or more of a forest's production may occur below ground in roots and mycorrhizae (Bowen 1984), but we define productivity based on the aboveground component. Although there has been concern that the aboveground component does not adequately estimate site productivity, there is recent evidence that productivity and nutrient cycling are controlled to an overwhelming extent by the functional characteristics of the dominant plants (Grime 1997). So, the traditional measurement of the tree bole as a means to determine productivity seems adequate. Based on these assumptions, a series of studies have been installed by the USDA Forest Service, Southern Research Station, with cooperators, to address the monitoring and ecophysiological questions related to long-term productivity of planted pine forests in the Region.

Monitoring Studies

We need an objective means for measuring long-term changes in potential site productivity of managed forests. Morris and Miller (1994) proposed three criteria for such studies: (1) tree growth differences must be attributable to true changes in site conditions and not merely on how site resources are partitioned, (2) enough time must pass so that early, possibly misleading trends can subside and more substantive, long-term effects can be seen, and (3) there must be adequate experimental control. Studies having approaches to meet these criteria are described.

1. The Long-Term Soil Productivity Study (LTSP)

In 1990, the USDA Forest Service began a Long-Term Soil Productivity (LTSP) study in major commercial timber types in National Forests across the country to address questions concerning the maintenance of soil productivity (Powers and Avers 1995). The LTSP study is predicated on the principle that the fundamental processes controlling productivity on a particular site involve interactions between soil porosity and site organic matter. Realizing that no single answer will apply to all situations, guidelines were developed that could be adapted to specific conditions of soil type and climatic regime. The 3 x 3 factorial experimental design creates gradients in soil porosity (none, medium and severe compaction) and site organic matter (bole, whole tree and whole tree plus litter removal). Nine combinations of soil compaction and organic matter removal were applied to 0.4 ha plots following the harvest of a mature stand of trees. Stem analyses of trees from the harvested stand were conducted to establish growth curves throughout the previous rotation so that comparisons between stand rotations could be made.

Ten installations of the study are installed in the Gulf Coastal Region: 3 in the Mississippi National Forests, 4 in the Risatchie National Forest of Louisiana, and 3 in the Texas National Forests, which represent a significant soil moisture gradient. Each installation consists of the nine treatment combinations and is planted with 10 genetically identified sources of loblolly pine. Initial soil conditions were measured on each plot and it was regenerated. To avoid confounding related to variable understory development, one-half of each treatment plot is maintained weed-free. This design ensures that vegetation will develop naturally on the second half. This provides the added

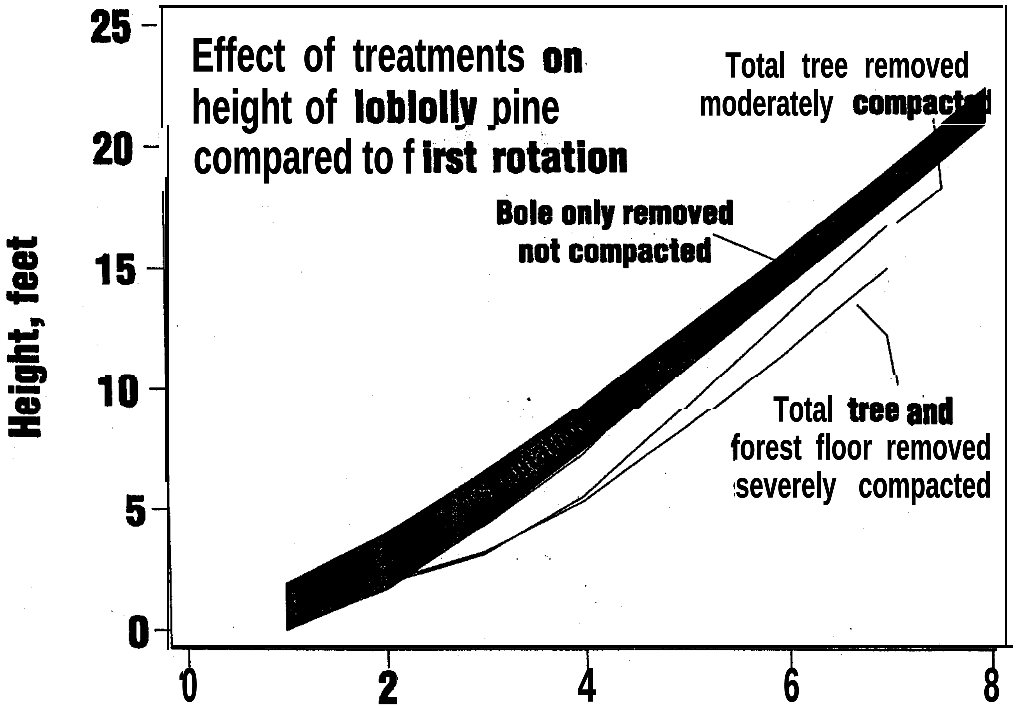

Figure 1. Height growth over time of loblolly pine on plots treated with three levels of organic matter removal and soil compaction and the estimated height of the previous stand at the same'ages. Plots are on the Palustris Experimental Forest in central Louisiana.

benefit of research into the long-term value of maintaining natural flora. Periodic measurements of trees alone, and total vegetation on all plots allows direct comparisons of productivity as measured by volume, dry weight and leaf area. Major soil properties (density, porosity, strength, organic matter, nutrient content, and moisture availability) also are measured at regular intervals and continuous meteorological records are kept as well. Thus, both relative and absolute measures of productivity can be related to changes in soil properties as influenced by treatment and climate. Each study site will be carried to full rotation to overcome the trends that may change with time.

At all sites, weed control resulted in more productive pines. The organic removal treatments have had the next greatest effect on pine growth. On soils with low levels of natural fertility in Mississippi, removal of all aboveground biomass reduced heights of the planted pines by 26 percent at age 3 compared to bole only removal. On a similar site in Louisiana, the growth loss was about the same, but it has appeared to recover with time. Thus by age 7, the difference between the least and most severe treatments was about 20 percent (Figure 1), which is still considered to be a significant management impact (Tiarks et al. 1997).

The soil water and soil temperature regimes are being measured at several of the sites in both the study plots and nearby unharvested stand. In addition, the fate of coarse woody debris on these sites will be followed in common materials placed in the unharvested stand. The impact of wood boring insects, ants, and termites on the rate of decay will be related to soil water and temperature regime, to better understand the release of nutri-

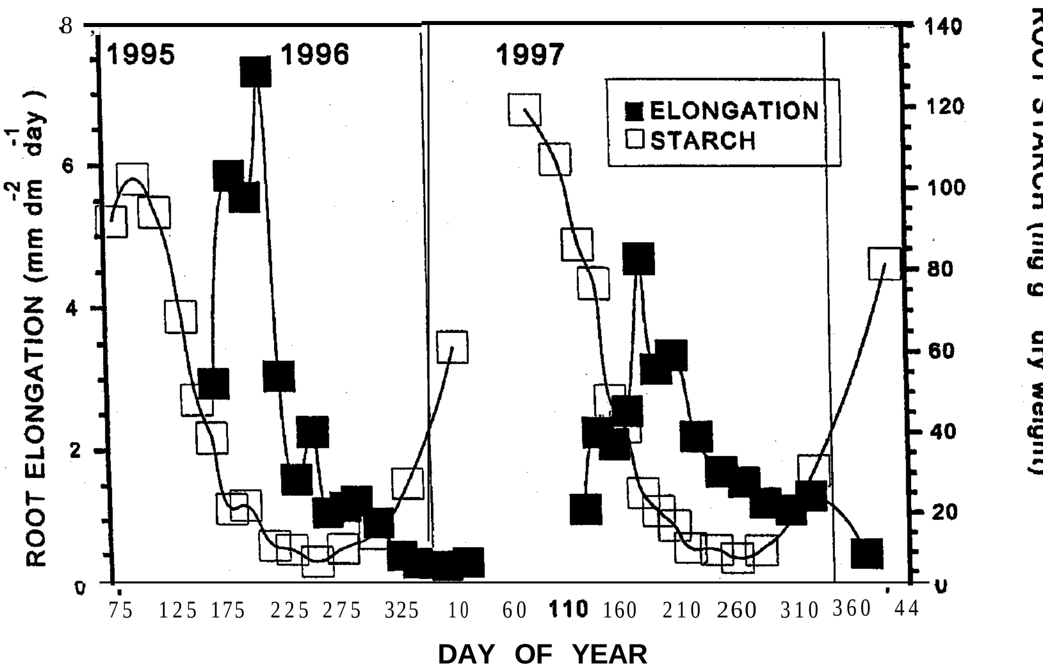

Figure 2. Net root elongation at 0 to 30 cm in rhizotrons, and fine root (≤ 5 mm diameter) starch concentration of loblolly pine planted in 1981. Values represent the mean of four stand management treatments.

ents from the woody material. Modeling will be used with this information to predict the effects of changes in nutrient dynamics on forest productivity.

The LTSP study was designed to meet the legal requirement established by the National Forest Management Act of 1976 that National Forest lands must be managed in ways that do not impair their long-term productivity (Powers et al. 1990). For this reason, little attention was given to the potential of using management to mitigate problems or enhance productivity. Another disadvantage of the design is that the disturbance impact cannot be associated directly with operational harvesting practices. These limitations to the LTSP study are being addressed in a partnership with forest industry in which long-term productivity studies are being installed on private lands (Carter et al. 1997). Some (but not all) treatments are in common with LTSP, and the same or similar measurement protocols are being followed. New treatments involving mitigation and amelioration have been added to address issues of site enhancement and recovery from negative impacts.

2. The Monitoring Productivity and Environmental Quality Study (MPEQ)

The cooperative long-term productivity project known as Monitoring Productivity and Environmental Quality in Southern Pine Plantations (MPEQ) was initiated in 1993 as a companion effort to the LTSP study. The current effort involves the USDA Forest Service, three forest industries and three universities. The objectives for the MPEQ project are: (1) provide creditable documentation of soil productivity in managed southern pine plantations, (2) provide a pooled database for linkage of industrial operations to the LTSP study, (3) provide a laboratory for assessing the impact of plantation management on soil processes and non-timber values,, and (4) identify and guide the development of new technologies. MPEQ is focused upon industrial plantations using more intensive management and shorter rotations than normally employed on the National Forests. A core design is used at all locations incorporating the hand harvesting, minimum impact treatment of the LTSP and three other treatments. Additional treatments are chosen by the cooperating industry, including conventional harvesting, site preparation and growth-enhancing technologies.

Each study site was occupied by a well-stocked stand of loblolly pine. Ages ranged from 18 to 31 years. The existing stands were documented by extensive sampling of soils and all aboveground vegetation. To document growth rate of the existing forest, 50 to 70 pine trees were felled at each location for detailed stem analysis. All plots were planted with loblolly pine seedlings. Pine growth and a variety of other soil and biological processes are being monitored throughout the next rotation.

Cooperating in the research are International Paper Company; Temple-Inland Forest Products Corporation; Willamette Industries, Inc.; School of Forestry, Louisiana Tech University; School of Forestry, Wildlife and Fisheries, LSU Agricultural Center; Department of Forest Science, Texas A&M University; and the USDA Forest Service, Southern Research Station.

Together the MPEQ and LTSP studies provide in-depth monitoring of nutrient budgets and ecosystem development on the loblolly pine plantations at 14 sites in the Gulf Coastal Region. Data from the MPEQ and LTSP locations are coordinated in a common database. This database provides valuable information on carbon and nutrient cycling in managed pine ecosystems. These studies should provide an increasing supply of interesting and useful data well into the next century, thus helping to ensure the sustainability of the southern pine forest resource and the many benefits and uses derived from it (Carter *et al.* 1997). Also, these studies provide a resource for conducting evaluations of biological processes that may be affected by application of silvicultural practices. There is need to supplement studies like LTSP and MPEQ with others that will provide even greater understanding of how forest management and environmental conditions interact. Such studies could help develop the ecophysiological understanding of how stands can be manipulated to mitigate influences of climate change.

Ecophysiological Evaluations

Critical to understanding how forest stands respond to climate change and how silviculture can be used to manipulate these responses is detailed knowledge of stand ecophysiology. First, the ecophysiological mechanisms that regulate carbon fixation and partitioning, and the acquisition of light, mineral nutrients and water by forest stands must be defined. Second, the response of these mechanisms to silvicultural practices must be understood. A study, Ecophysiology of Plantation Loblolly Pine (EPLP), is being conducted in a loblolly pine stand to provide this biological understanding.

Climate, edaphic and biotic conditions control physiological processes in forest trees. Interaction among physiological processes, in turn, controls tree growth and tolerance to environmental stress. Thus, climate, edaphic factors and biotic variables determine the survival, development and productivity of forest stands. Once identified, quantification of important environmental variables and ecophysiological mechanisms can be used to predict forest stand dynamics in response to current and future climate scenarios.

The Ecophysiology of Plantation Loblolly Pine Study (EPLP)

This study is being done to improve our knowledge of how environmental variables and ecophysiological mechanisms, either directly or, by interaction, regulate forest ecosystem function. We are focusing on loblolly pine plantation growth as a measure of ecosystem function. Our first objective is to contribute to the limited information available on the fascicle and root system physiology and growth of southern pine trees in forest stands. The second objective of this study is to use simultaneous measurement of above and belowground processes and environmental variables to hypothesize key variables and mechanisms that control stand growth. Third, by conducting these intensive observations in replicated plots subjected to operational silvicultural treatments, we will have the information necessary to hypothesize effective management alternatives in a changing climate. Finally, the potential exists for our work to refine the concepts that guide above and belowground inputs to existing forest stand process models, and subsequently, improve the quality of regional models that predict forest productivity in response to climate change.

1. EPLP Research Highlights

This research is being implemented in a 17-year-old loblolly pine plantation located on the Palustris Experimental Forest in central Louisiana. In 1981, container-grown loblolly pine seedlings from a genetically unimproved source were planted (1.8 x 1.8 m) . The soil is a Beauregard silt loam that is naturally low in phosphorus (Kerr et al. 1980). In the spring of 1988, 12-0.06 ha treatment plots, 13 rows of 13 trees each, were established (Haywood 1994). Two levels of thinning (not thinned: 2,732 trees per ha; thinned: 721 trees per ha) and two levels of fertilization (not fertilized; fertilized: 135 kg N plus 150 kg P per ha) were randomly applied to the plots in a 2 x 2 factorial design with three replications. Competing vegetation is continuously controlled by spot applications of glyphosate.

Stand density and fertilization treatments were reapplied six growing seasons after initial application. In spring of 1995, the previously thinned plots (25 m^2 per ha) were thinned from below to 30 percent of maximum stand density index (not thinned: 42 m^2 per ha; thinned; 15.6 m^2 per ha) (Dean and Baldwin 1993). Based on foliar mineral nutrient concentrations in August 1993, a fertilizer recommendation was developed for the previously fertilized plots. In spring of 1995, these plots were fertilized (200 kg N, 50 kg P plus 50 kg K per ha], and nonfertilized plots were not fertilized.

Two replications of the study were chosen for intensive ecophysiological measurements. Steel towers and wooden walkways were erected to access the upper and lower one-third of the crowns of at least eight trees per plot. Simultaneous observations of above and belowground tree growth and development, branch environment and physiology, soil environment, and stand climate were initiated in March 1993 and have continued to the present. Internode and fascicle expansion, fascicle retention and foliated branch length are quantified weekly in the upper and lower crown. The net photosynthesis, stomata1 conductance, transpiration and water potential of fascicles in the upper and lower crown are measured at twice per month intervals. The temperature, photosynthetically active radiation and relative humidity near branches in the upper and lower one-third of tree crowns and stand climate, are monitored electronically. Tree heights and diameters at breast height are measured, and stand basal areas and volumes are calculated at three-month intervals.

Research results have shown that fascicle physiology and growth are not only affected by silvicultural treatment, but are strongly affected by location in the crown, For example, Gravett et *al.* (1997) found that light availability and rates of net photosynthesis were greater in the upper crown than in the lower crown of the thinned and unthinned plots. Light availability and net photosynthesis were greater on the south, rather than the north side of the trees. By conducting these measurements intensively throughout the growing season, we have found that physiological and growth processes are characterized by distinct seasonal patterns that, with stand environmental data, have allowed us to hypothesize interactions among environmental variables and physiological processes that control tree growth.

Five Plexiglas rhizotrons are maintained on each plot of two replications to observe root system growth and development in the 0 to 30 cm depth of the soil (Sword 1998a). At each two-week measurement interval, net new root elongation is quantified and new roots are classified morphologically by diameter and branching pattern. At approximately three-week intervals, roots and foliage are sampled and analyzed for starch, glucose and sucrose. Soil temperature and water content at 5, 15 and 30 cm depths are quantified daily. We have characterized the seasonal pattern of loblolly pine root growth in the four stand environments, and have determined that physiological and environmental conditions created by silvicultural treatments affect root growth and may influence forest growth by affecting soil resource uptake (Sword 1998a, 1998b).

With simultaneous measurement of above and belowground variables, we are able to observe the synchrony of physiological and growth processes in the crown and root system, and show how they are influenced by the environment. Early observations suggest that together with branch and root phenological data and knowledge of source/sink relations, measurement of carbohydrate fluxes in the foliage and roots could be used to identify the key regulators of root system growth and development. Our pattern of fine root starch depletion, and growth in spring suggests that stored starch is a major source of glucose for root metabolism during the peak period of root growth (figure 2).

1. EPLP Research Direction

We are developing methodology to expand our fascicle-level data to express carbon fixation and water flux at the branch, crown and stand levels. Early work indicated that fascicle physiology and branch carbon fixation, calculated using branch morphology and fascicle net photosynthesis, were strongly affected by silvicultural treatments and crown strata (Gravatt 1994, Gravatt et *al.* 1997). As a result, to express stand-level physiology, we recently increased the resolution of our measurements to include data from three crown strata and four cardinal directions.

Methods have become available to quantify transpiration as the flux of water through the vascular tissue of woody plants (Vertessy et *al.* 1997). With this new technology, we are attempting to "scale-up" fascicle physiological measurements to express stand-level processes. Our objectives are to compare: (1) branch transpiration quantified by the water flux method and calculated data from fascicle transpiration and branch morphology, and (2) crown transpiration quantified by the water flux method and calculated from branch water flux and crown morphology. Information obtained using this technology is potentially valuable in the expression of physiological processes at the stand level. This information should prove useful in adjusting interpretation of leaf and branch level data from previous studies to the stand level.

Preliminary efforts to link root growth and soil environmental data indicate that extension of the peak period of root growth in summer may be related to water availability (Sword 1998b). However, the importance of this relationship relative to root system function is unknown because, although periods of water deficit have been experienced, no evidence of water stress has been detected in fascicle physiological measurements (Tang, personal communication). At the time of water flux measurements, the water content of the soil profile will be measured by depth to determine the pattern of water flux to, and from, the soil. This information, together with aboveground water flux and root growth and development data, will increase our knowledge of the seasonal distribution and function of roots in the soil profile, and reveal how interactions among root phenology, distribution and function respond to environmental change.

The seasonal dynamics of leaf area is one of the important regulators of stand carbon fixation

(Stenberg et al. 1994). Furthermore, seasonal leaf area is an important variable in many process models used to predict stand and regional forest productivity. New methods of obtaining this information are needed for model development and would lead to improvement of our current predictive ability. In 1995 when the second thinning was conducted, a detailed analysis of crown and stem structure was conducted on a subset of trees from each plot (Yu 1996). Significant relationships were found between tree leaf area and sapwood area. The most accurate predictions of leaf area were obtained from sapwood areas restricted to the most recent three years of diameter growth. Since water flux is greatly influenced by leaf area, these results suggest that there is potential for use of this technology for frequent leaf area determinations.

The Choice of Species (COS) Study

During the years of 1954 through 1958, the USDA Forest Service with the help of public and private forestry organizations established 113 installations of the Choice of Species (COS) study in Louisiana and Mississippi to compare growth of longleaf (*Pinus palustris* Mill.), slash (*P. elliottii* Engelm.), loblolly, and shortleaf (*P. echinata* Mill.) pines on a broad range of sites. The original purpose of the study was to help decide which southern pine species should be planted on a particular site. Each installation contained 3 plots of each species, except only about half included shortleaf pine because they fell outside the range of this species. Each plot contained 49 (in Louisiana) or 64 (in Mississippi) measurement trees with two border rows around each plot. Planting was on a 1.82 x 1.82 m spacing.

Plots were inventoried at ages 1, 3 (MS) or 5 (LA), 10, 15, 20, and 25 years. Measurements focused on differences among species in survival, growth (height, diameter, and volume), and the incidence of fusiform rust. Today, about 70 installations remain. A number of publications resulted from the study, e.g., Shoulders (1976) and Shoulders and Tiarks (1980).

These existing plots became the focus of a new effort in 1990 to (1) develop a better understanding of the relationship between edaphic and climatic factors and the growth of loblolly and slash pine, and (2) evaluate the use of dendrochronology for investigating the response of loblolly and slash pine to variation in climate. In all existing installations, soil profiles have been described and sampled in each study plot. Soil series designations have been assigned where possible and physical and chemical analyses of the soil samples are being made. In addition, growth and survival databases have been reviewed and reconciled. Remeasurement of the plots and intensive collections of increment cores have been completed. An excellent opportunity exists to use this database to develop knowledge of the interactions among climate, soils, and tree growth in the Gulf Coastal Region.

Conclusions

Planted forests represent the best hope for meeting the nation's wood requirements while maintaining quality of life throughout the 21st century (Powers *et* al. 1996). Merchantable yields stand at historical highs because of advances in genetic selection, site preparation, planting techniques, stand tending, harvesting methods and manufacturing efficiency. These yields cannot be sustained unless the productive capacity of the soil systems are maintained and it is understood how climate change will influence forest stand development. Understanding the impact of management practices and climate change on potential productivity is necessary for sustainable forestry. Solutions and understanding can be found through cooperative, integrated programs that pool resources and capabilities of the government, forest industry, and university community.

Long-term studies such as those described here offer great potential to understand the biology of how forest stands respond to manipulation and to varying environmental conditions. These studies can be the basis of developing greater knowledge of effects of climate change on the productivity and sustainability of forests in the Gulf Coastal Region.

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