

PRODUCTIVITY AND NUTRIENT MANAGEMENT CONCEPTS and FERTILIZATION PRACTICES in SOUTHERN PINE PLANTATIONS

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INTRODUCTION

The southeastern United States produces more industrial timber than any other region of the world from a forest base that now comprises almost one-half of the world's industrial forest plantations (Prestemon and Abt, 2002). Over the next several decades, wood demands are expected to continue to increase and the land base used for wood production is projected to continue to shift from natural forests owned by non-industrial private landowners to pine plantations. Typically, plantations have been owned and managed principally by forest industry but now increasingly they are owned by pension funds and other investors. Although softwood removals exceeded growth in many parts of the South in the 1990's (Cubbage et al. 1995), recent projections indicate that growth should exceed harvest removals within the next decade in most areas as the productive plantation land base continues to increase (Prestemon and Abt, 2002). Clearly, southern forests are undergoing dramatic changes in ownership and use. The area in pine plantations and the intensity at which these plantations are managed are both responding to and affecting the supply and price of wood providing much uncertainty in future predictions.

Historically, forest landowners (both industrial and non-industrial) have focused on minimizing per acre costs associated with plantation establishment and tending. This approach has resulted in millions of planted acres in the southeastern United States with growth rates averaging less than 5 green tons/acre/year. These growth rates are substantially lower than many other forest plantations in the world. Fortunately, theoretical models (Sampson and Allen 1999, Landsberg et al 2001), empirical field trials (Allen and Lein 1998, Martin et al. 1999, Amateis et al. 2000, Jokela et al. 2000, Borders and Bailey 2001, Martin and Shiver 2002) and operational experience show that these growth rates are well below what is possible in the southeastern United States. With investment in appropriate intensive plantation silvicultural systems, growth rates exceeding 10 tons/acre/year are biologically possible and financial attractive for a broad range of site types. The greater inputs typically associated with intensive silviculture may increase per acre costs; however, the resultant increases in production

can substantially reduce production costs per ton of wood when variable (treatment) and fixed (land and annual management) costs are considered (Figure 1).

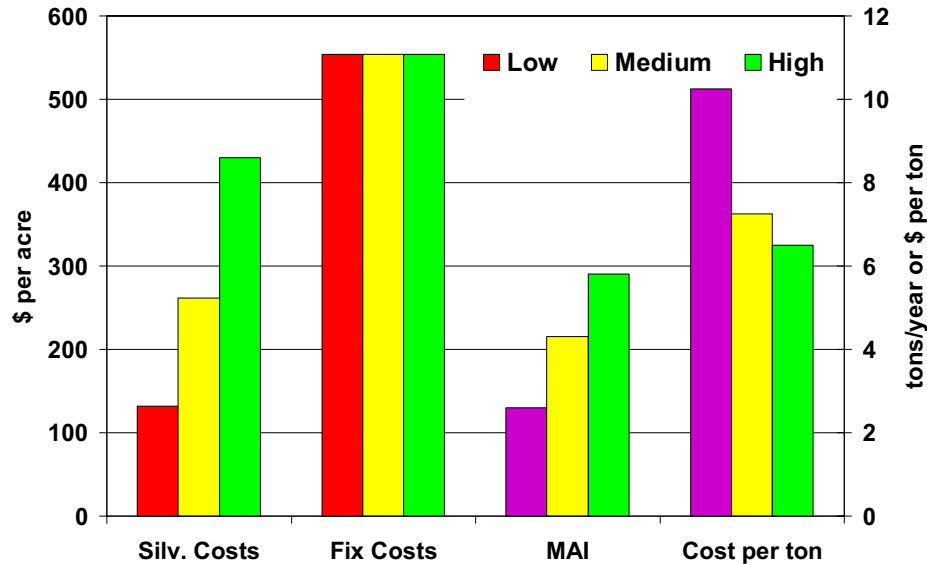


Figure 1. Costs and benefits associated with intensive silviculture.

CONCEPTS

It is now generally accepted that much of the variation in biomass and wood production can be accounted for by variation in light interception. (Landsberg and Gower 1997, Cannell 1989, Linder 1987). Light interception is principally a function of the amount of leaf area and the duration of leaf area display. Differences in individual tree crown architecture and stand canopy structure can also affect light interception. Empirical data from field studies with Scots pine, Norway spruce (Bergh et al 1998, Linder 1987), radiata pine (Linder et al. 1987, Benson et al. 1992, Snowdon and Benson 1992), southern pines (Colbert et al. 1990, Vose and Allen 1988, Albaugh et al. 1998), and Eucalyptus globulus (Pereira et al. 1994) have shown that leaf area and consequently wood production are below optimum levels in many areas of the world (Figure 2). Low nutrient availability is a principal factor causing suboptimal levels of leaf area in many areas (Albaugh et al 1998, 2004, Colbert et al. 1990, Linder 1987, Vose and Allen, 1988). Low soil water availability, high vapor pressure deficits, and high temperatures have also been shown to adversely affect leaf area production and/or retention (Benson et al. 1992, Hennessey et al. 1992, Pereira et al. 1994, Teskey et al. 1987).

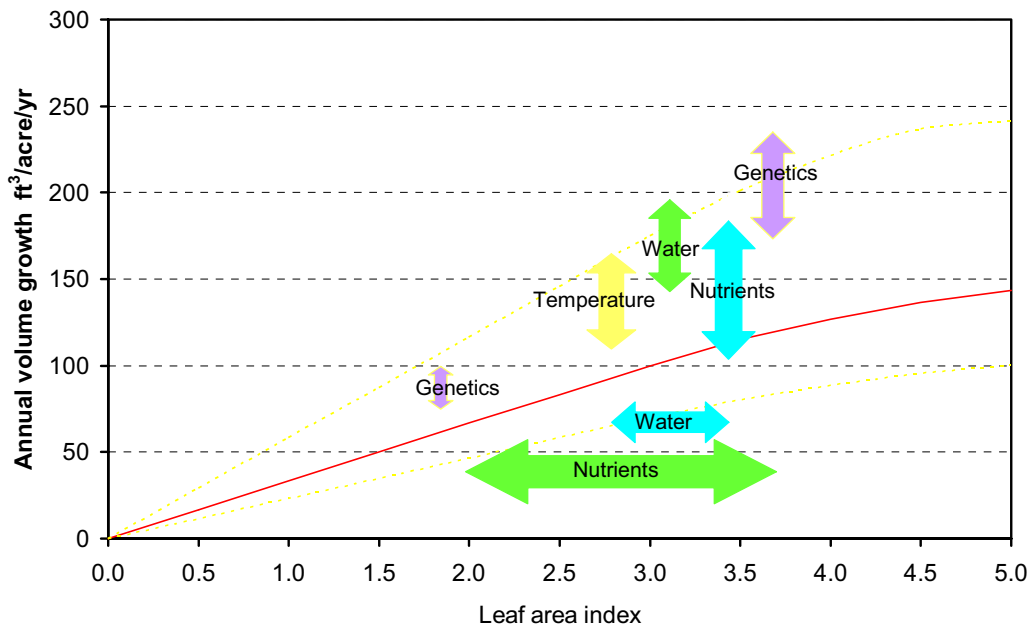


Figure 2. Relationship between annual volume growth and leaf area in southern pine plantations in the Southeast US and factors that are known to affect productivity.

The variation in production per unit of leaf area (generally defined as the slope of the wood production – leaf area relationship and referred to as growth or leaf area efficiency) can also contribute to the variation in production. Growth efficiency can vary due to differences in photosynthetic efficiency, respiration, and partitioning to various biomass components. Improved nutrient and water availability has been shown to increase photosynthetic efficiency (Linder 1987, Murthy et al 1996), and above ground productivity proportionally more than below ground productivity in stand level studies (Albaugh et al. 1998, 2004, Gower et al. 1992, Haynes and Gower 1995). On an individual site basis, changes in growth efficiency generally do not contribute to as much to changes in productivity as changes in leaf area. However, when species (e.g. loblolly pine in the Southeast or radiata pine in Chile) are planted across large areas with substantial regional differences in precipitation and temperature, region variation in growth efficiency may be substantial (Figure 2, Sampson and Allen 1999).

What are the limitations to pine production in the southeastern U.S.? It is clear that leaf area levels are low enough in many stands that the capture of light is restricted resulting in poor productivity (Vose and Allen 1987, Albaugh et al. 1998, 2004, Jokela and Martin 2000). In addition, growth efficiency, the production of stemwood per unit of leaf area, is also less than optimum. From a resource availability perspective, water availability, whether too little or too much, has historically been

considered the principal resource limiting pine productivity in the South. While, this is true for most sites for young seedling (Dougherty and Gresham 1988) and for specific soil types (e.g. very wet or very dry soils) throughout the rotation, recent analyses suggest that chronically low levels of available soil nutrients, principally nitrogen and phosphorus, and additionally potassium and boron on loamy or sandy soils, are more limiting to growth in established stands than water limitations (Albaugh et al. 1998, 2004, Sampson and Allen 1999, Jokela and Martin 2000). Low soil nutrient supplies reduce leaf area development and growth efficiency, and consequently, stand production (Figure 2). The good news is that most nutrient limitations are easily and cost effectively ameliorated with fertilization.

The key to optimizing leaf area and growth efficiency and thereby achieving optimum value is the development and implementation of site specific silvicultural prescriptions. Depending on the site and market conditions, silvicultural treatments may include planting high quality seedlings or plantlets from the best families of the right species to a site where competing vegetation has been suppressed and where the soil may have been tilled and/or fertilized to improve early tree growth. Application of appropriate silvicultural treatments does not stop with plantation establishment. Optimum value production on most sites will only be possible with competing vegetation suppression, repeated nutrient additions, thinning, and pruning – treatments that provide needed resources to the appropriate number of quality crop trees. Forest managers are now recognizing that intensive plantation silviculture is like agronomy; both the plant and the soil need to be actively managed to optimize production. Fortunately, financially attractive options exist to increase production through the management of both genetic and site resources. Improving stand nutrient supply through fertilization is a very attractive silvicultural option as nutrient limitations are very widespread.

Why are nutrient limitations so common? Simply, nutrient limitations develop when a stand's potential nutrient use cannot be met by soil nutrient supply. Consideration of a stand's potential nutrient use and nutrient supply indicates a large disparity between nutrient needs and supply in southern pine stands (Figure 3, Allen et al., 1990). Typically, nutrient availability is rather high following harvesting and site preparation as these disturbances provide suitable conditions for rapid decomposition and release of nutrients from the accumulated forest floor and slash material. Use of nutrients by crop trees is minimal owing to their small size, low leaf area, and lack of site occupancy. However, as leaf area development and stand growth accelerates, use of nutrients increases rapidly. At the same time, the supply of readily available nutrients is being rapidly sequestered within the accumulating forest floor and tree biomass. Furthermore, as the canopy closes, the environmental conditions conducive to high nutrient availability are no longer present (Piatek and Allen 1999, 2001). Consequently, a stand's nutrient requirement for maximum growth generally outstrips soil supply (particularly for N) around time of canopy closure. As

nutrient supply diminishes, leaf area production and, in turn, growth become regulated (and limited) by the available nutrient pool. It is not surprising then, that the majority of field trials in intermediate-aged southern pine stands (~8 to 20 years old) have shown strong responses to additions of N and P (Martin et al. 1999, Amateis et al. 2000). In young stands, the development of nutrient limitations is still possible when levels of available nutrients (particularly P) in the soil are low and the soil volume exploited by roots is small. In addition, as other silvicultural treatments (e.g. vegetation control and/or tillage) are used to improve water availability, crop tree growth and use of nutrients will be increased at young ages. Fertilization will then be needed to sustain rapid growth on all but the most fertile sites.

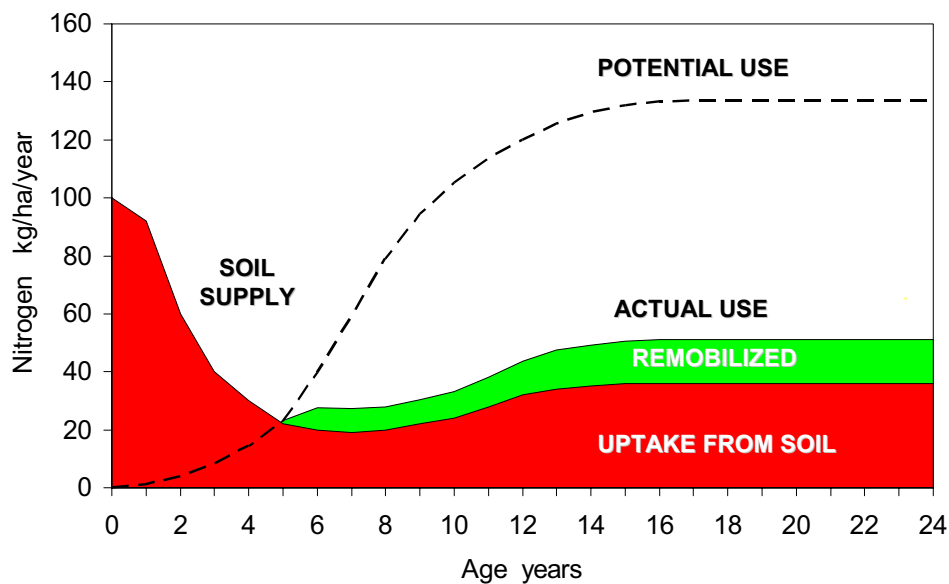


Figure 3. The concept of soil nitrogen supply and a stand’s potential and actual use of nitrogen as related to stand development (age).

FERTILIZATION PRACTICES

Management of pine plantations in the southeastern United States is undergoing revolutionary change. Intensive silvicultural regimes are now being implemented that include deployment of genetically improved planting stock, tillage, herbaceous and woody vegetation control, and multiple fertilizer applications (Allen, 2001). The area being fertilized annually is indicative of this change. In 1990, about 200,000 acres of pine plantations were fertilized; however, in 2002, over 1.5 million acres were fertilized (Figure 4), a fraction of the over 30 million acres of pine plantations.

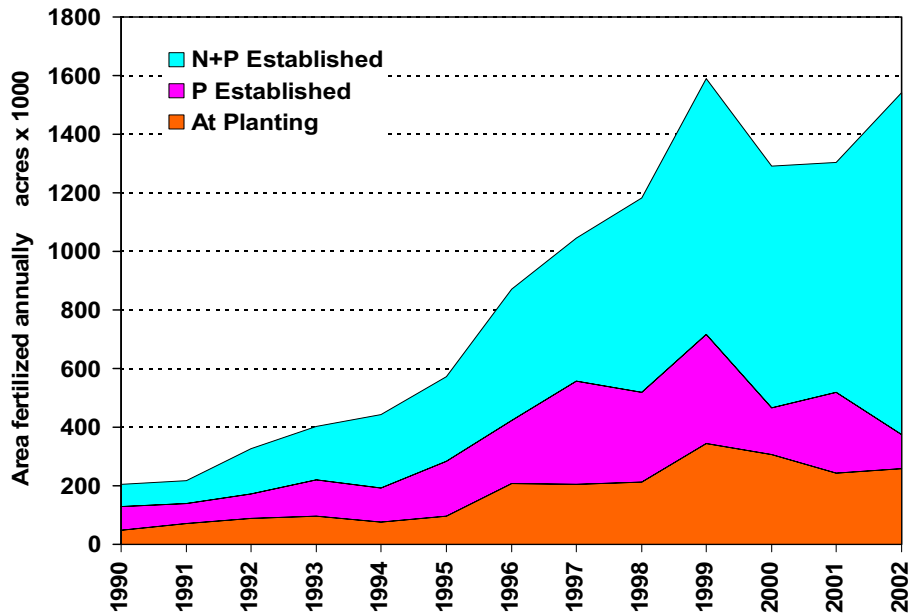


Figure 4. Area of southern pine plantations annually fertilized in the southeastern United States (Forest Nutrition Cooperative data).

The benefits of early P fertilization on the poorly drained P-deficient flats of the lower coastal plain have long been recognized. Volume growth gains averaging 40 to 50 ft³/acre/year (3 to 4 m³/ha/year) are typical on severely P-deficient sites. Because the duration of response to a single application of 50 lbs/acre of P may last for 20 or more years (Pritchett and Comerford 1982), P fertilization on deficient sites may yield volume gains of over 100% and consequently is viewed as an improvement in site quality. Site index gains (25-year base) of 6 to 10 feet or more are typical when P is applied at or near time of planting (Gent et al. 1986). More recently, results from several Forest Nutrition Cooperative trials have shown that large areas of well-drained sites on the upper Gulf Coastal plain are also P-deficient (Figure 5; Allen 1990, Allen and Lein 1998). Unlike the well-drained sites on the Atlantic coastal plain, many Gulf coastal plain sites have never been in row crops and, consequently, have not been fertilized.

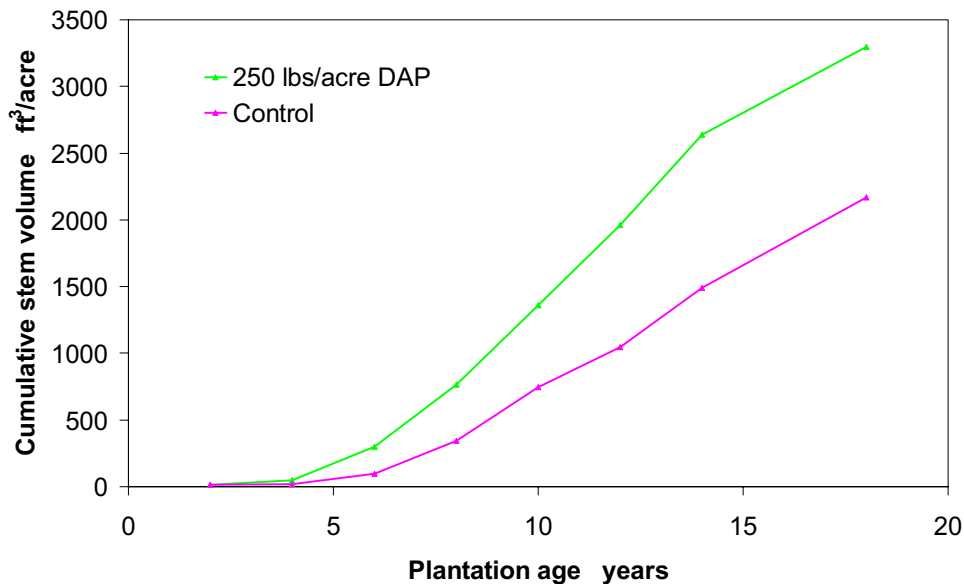


Figure 5. Volume growth with and without P application at time of planting on a well drained loamy soil (Forest Nutrition Cooperative data).

Identification of stands in need of early fertilization is based on landscape/soil type, geology, soil and foliar tests, and experience. The critical value for soil P below which a fertilizer response is expected is 6 ppm (Mehlich-3 extraction procedure). Critical values for foliar P concentrations vary by species and range from 0.09% for slash pine and 0.11% for loblolly pine (Allen 1987, Jokela et al. 1991). The sources of fertilizer P that are typically used include diammonium phosphate (DAP), triple superphosphate (TSP), and rock phosphate. DAP is now the most widely used source for fertilization at time of planting. Rates of application vary from 25 to 50 lbs/acre of elemental P (125 to 250 lbs/acre of DAP). In 2002, almost 250,000 acres received fertilizer at or near time of planting (Figure 4).

By age 5 or earlier, a plantation's potential to use N and P typically outstrips the available soil supply resulting in restricted leaf area development and growth (Figure 3, Allen et al. 1990). By time of canopy closure, stands are generally very responsive to additions of N or N+P rather than P alone, as long as gross P deficiencies were ameliorated at or soon after planting. Volume growth responses vary depending on stand/site attributes and the rates of N and/or P applied. Results from an extensive series of intermediate-aged fertilizer trials in loblolly pine stands established by the Forest Nutrition Cooperative indicate that over 85 percent of the stands fertilized were responsive to additions of N+P. Growth gains averaging 30% (50 ft³/acre/year) over a six-year period following a one-time application of 200 lbs/acre

N and 25 lbs/acre P are typical (Figure 6). Responses of over 100 ft³/acre/year are possible on some sites. For the majority of stands, both N and P are deficient with responses to additions of N+P much greater than the additive effects of the two elements applied alone (i.e. N and P additions are synergistic).

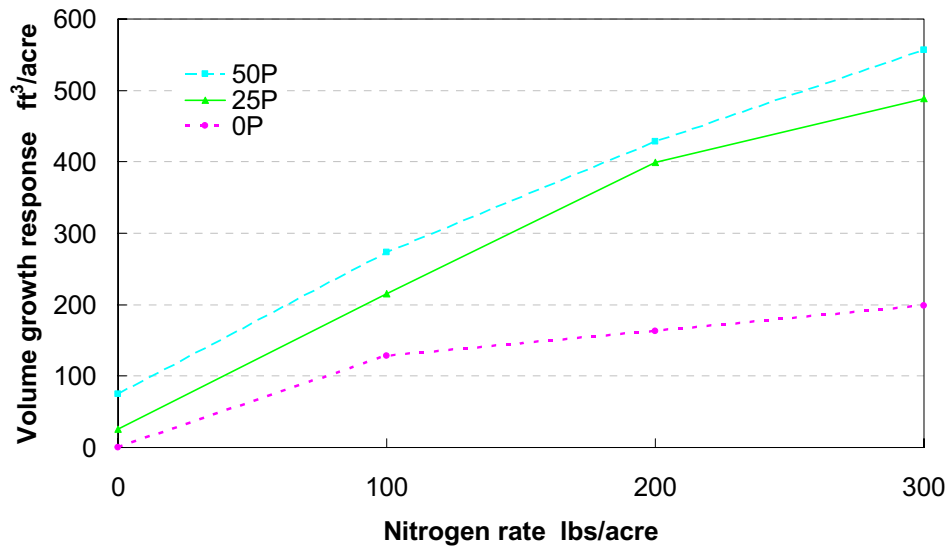


Figure 6. Volume growth response to N and/or P additions in intermediate-aged loblolly pine plantations (Forest Nutrition Cooperative data).

In intermediate-aged stands, little response is typically observed to additions of P alone except on very P-deficient sites as indicated by low foliar P concentrations and very low leaf areas. Applications of ~200 lbs/acre of DAP (labeled as P established in Figure 4) are typically used as the remedial treatment in these stands. Additions of N alone can actually be detrimental to growth on these severely P-deficient sites.

The large increase in area fertilized has been due primarily to the dramatic increase in fertilization of intermediate-aged stands (Figure 4). On most sites, a prescription of between 150 to 200 lbs/acre of N plus 25 lbs/acre of P is used for loblolly or slash pine. Lower doses of N are recommended for longleaf pine (Blevins et al 1996). Typically, this treatment is applied as an application of DAP and urea to provide the additional N required to reach the desired N rate. Although most intermediate-aged stands will be biologically responsive to N+P fertilization, financial returns are strongly dependent on fertilizer cost, the product mix, and stumpage price that can be realized for the additional wood produced. Application of 200 lbs/acre N plus 25 lbs/acre P presently costs from \$65 to \$90 per acre. At this price, fertilization is a very attractive investment with internal rates of return exceeding 15% or

more. Until recently, fertilization has been delayed until after the first or second thinning to maximize returns on investment. This is now changing as the need for nutrients earlier in a plantation's life is recognized and increasing wood values have made even early fertilization a very attractive financial investment.

The diagnostic techniques for identifying intermediate-aged stands that will be biologically responsive to fertilization have recently undergone substantial revision. In the past, stand attributes (e.g. basal area and site index), soil/landscape type, foliar concentrations (Colbert and Allen 1996), and experience were used together to identify responsive stands and prescribe the appropriate elements and rates to apply (Allen 1994). Unfortunately, the ability to predict the responsiveness of an individual stand was limited. This situation has now changed with the application of recent Forest Nutrition Cooperative research that quantifies the linkages among stand productivity, leaf area, and nutrient availability (e.g. Albaugh et al. 1998). Differences between a stand's current leaf area and its potential leaf area are now being used to estimate responsiveness to nutrient additions and the appropriate timing, elements, and rates of application. Quite simply, leaf area of a fully stocked stand (basal area >100 ft²/acre) should be 3.5 or greater; otherwise, the stand is probably in need of N+P. The probability and magnitude of response will be greater at lower leaf areas.

INTEGRATED SILVICULTURAL SYSTEMS

Much effort is now underway to understand the interactions among the numerous silvicultural treatment options available at or near time of planting including genetic selection and cultural treatments (McKeand et al. 1997) and among cultural treatments such as tillage, vegetation control, and fertilization (Allen and Lein 1998, Jokela et al. 2000). For example, the ability to acquire and utilize nutrients differs among species and among genotypes, with slash pine and longleaf pine having lower nutrient use than loblolly pine. Consequently, loblolly pine is generally more responsive to intensive culture than either slash pine or longleaf pine. Where two silvicultural treatments affect nutrient availability and/or the allocation of nutrients to the crop trees in a similar manner, less than additive effects may be observed. For example, where both intensive vegetation control and fertilization result in greater nutrient supply, a less than additive response has been observed with slash pine on wet sandy sites. In contrast, the growth response to hardwood control and fertilization in loblolly pine stands on upland sites is typically more than additive (Figure 7). Without control, hardwoods also respond to fertilizer resulting in increased competition for light and water resources with pine crop trees. In many established stand situations, responses to fertilization, thinning, and vegetation control have been additive (Albaugh et al 2003).

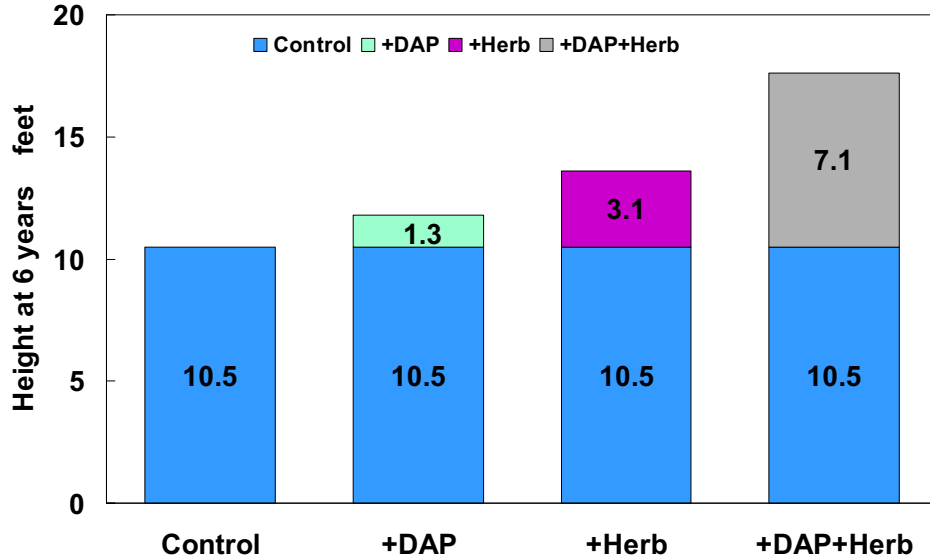


Figure 7. Six-year volume growth with and without fertilization and vegetation in a loblolly pine plantation on an well-drained upland site (Forest Nutrition Cooperative data).

FUTURE OPPORTUNITIES

The growth potential of southern pines planted in the southeastern United States is very high, much higher than commonly thought just a few years ago. Our challenge now is to develop and implement the appropriate silvicultural systems to realize this potential in a cost-effective and environmental sustainable manner. The Forest Nutrition Cooperative is aggressively pursuing several opportunities for improving plantation growth and value through the management of site resources including:

- developing and implementing new techniques to resource limitations by integrating spatially explicit spectral reflectance imagery, soils, geology, and climatic data,
- identifying sites where nutrients other than N and P are limiting growth and developing the appropriate prescriptions to ameliorate these limitations,
- understanding how nutrient availability and plant biochemistry interact to affect wood quality, stem quality, and susceptibility and resistance to insects and diseases,
- investigating use of more effective fertilizers and other nutrient sources to ameliorate nutrient limitations,
- developing advanced growth and yield systems and decision support models that accurately reflect silvicultural treatment impacts,
- and understanding the impacts of intensively managed plantations within a landscape context.

The close linkages among the applied research, fundamental research, and continuing education efforts at the Forest Nutrition Cooperative provide an excellent environment for addressing

pertinent research questions and immediately incorporating research results into management strategies. These close linkages are the hallmark of our cooperative program, and coupled with our extensive field trial base, position the Forest Nutrition Cooperative to continue a leadership role in developing integrated silvicultural systems approaches for plantation management.

REFERENCES CITED

- Albaugh, T.J., H. L. Allen, P. M. Dougherty, and K. H. Johnsen. 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *For. Ecol. Manage.* 192:3-19.
- Albaugh, T.J., H.L. Allen, B.R. Zutter, and H.E. Quicke. 2003. Vegetation control and fertilization in midrotation *Pinus taeda* stands in the southeastern United States. *Ann. For. Sci.* 60: 619-624.
- Albaugh, T.J., H.L. Allen, P.M. Dougherty, L.W. Kress, and J.S. King. 1998. Leaf-area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.* 44:317-328.
- Allen, H.L. 2001. Silvicultural Treatments to Enhance Productivity. Chap. 6, In J. Evans (ed). *The Forests Handbook. Volume II.* Blackwell Science Ltd., Oxford, UK. 382 pp.
- Allen, H.L. 1994. Enhancing southern pine productivity with fertilization. *The Consultant*(Summer):12-17.
- Allen, H.L. 1990. Manipulating loblolly pine productivity with early cultural treatment. pp. 301-317, In: S.P. Gessel, D.S. Lacate, G.F. Weetman, and R.F. Powers (eds.). *Sustained Productivity of Forest Soils. Proceedings of the 7th North American Forest Soils Conference, University of British Columbia, Faculty of Forestry, Vancouver, B.C.*
- Allen, H.L. 1987. Forest fertilizers: Nutrient amendment, stand productivity, and environmental impact. *J. For.* 85(2):37-46.
- Allen, H.L. and S. Lein. 1998. Effects of site preparation, early fertilization, and weed control on 14-year old loblolly pine. *Proc. South. Weed Sci. Soc.* 51:104-110.
- Allen, H.L., P.M. Dougherty, and R.G. Campbell. 1990. Manipulation of water and nutrients - practice and opportunity in southern U.S. pine forests. *For. Ecol. Manage.* 30:437-453.
- Amateis, R. L., J. Liu, M. J. Ducey and H. L. Allen. 2000. Modeling response to midrotation nitrogen and phosphorus fertilization in loblolly pine plantations. *South. J. Appl. For.* 24:207-212.
- Bergh, J., S. Linder, T. Lundmark, and B. Elfving. 1998b. The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. *For. Ecol. Manage.*
- Benson, R.E., B.J. Myers, and R.J. Raison. 1992. Dynamics of stem growth of *Pinus radiata* as affected by water and nitrogen supply. *For. Ecol. Manage.* 52:117-138.
- Blevins, D.P., H.L. Allen, S.R. Colbert, and W.E. Gardner. 1996. Nutrition Management for Longleaf Pinestraw. Woodland Owner Note No 30. North Carolina Cooperative Extension Service. North Carolina State University. Raleigh. NC.

- Borders, B.E. and R.L. Bailey. 2001. Loblolly pine--pushing the limits of growth. *South. J. Appl. For.* 25:69-74.
- Cannell, M.G.R. 1989. Physiological basis of wood production: a review. *Scand. J. For. Res.* 4:459-490.
- Colbert, S.R. and H.L. Allen. 1996. Factors contributing to variability in loblolly pine foliar nutrient concentrations. *South. J. Appl. For.* 20(1):45-52.
- Colbert, S.R., E.J. Jokela, and D.G. Neary. 1990. Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *For. Sci.* 36:995-1014.
- Cubbage, F.W., T. Harris, Jr., R.C. Abt, and G. Pacheco. 1995. Timber supply in the South: Where is all the wood? *J. For.* 93(7):16-20.
- Dougherty, P.M. and C.A. Gresham. 1988. Conceptual analysis of southern pine plantation establishment and early growth. *South. J. Appl. For.* 12:160-166.
- Gent, J.A., H.L. Allen, R.G. Campbell, and C.G. Wells. 1986. Magnitude, duration, and economic analysis of loblolly pine growth response following bedding and phosphorus fertilization. *South. J. Applied For.* 10:124-128.
- Gower, S.T., K.A. Vogt, and C.C. Grier. 1992. Carbon dynamics of Rocky Mountain Douglas-fir: influence of water and nutrient availability. *Ecol. Monogr.* 62:43-65.
- Haynes, B.E., and S.T. Gower. 1995. Belowground carbon allocation in nonfertilized and fertilized red pine plantations in northern Wisconsin. *Tree Phys.* 15:317-325.
- Hennessey, T.C., P.M. Dougherty, B.M. Cregg, and R.F. Wittwer. 1992. Annual variation in needlefall of a loblolly pine stand in relation to climate and stand density. *For. Ecol. Manage.* 51:329-338.
- Jokela, E.J. and T.A. Martin. 2000. Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. *Can. J. For. Res.* 30:1511-1524.
- Jokela, E.J., D.S. Wilson, and J.E. Allen. 2000. Early growth responses of slash and loblolly pine following fertilization and herbaceous weed control treatments at establishment. *South. J. Appl. For.* 24:23-30.
- Jokela E.J., H.L. Allen, and W.W. McFee. 1991. Fertilization of southern pines at establishment. Chap. 14 In: M. Duryea and P. Dougherty (eds.) *Forest Regeneration Manual*. Kluwer Academic Publishers. Netherlands.
- Landsberg, J.J., K.H. Johnsen, T.J. Albaugh, H.L. Allen, and S.E. McKeand. 2001. Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci.* 47:43-51.
- Landsberg, J.J. and S.T. Gower. 1997. *Application of Physiological Ecology to Forest Management*. Academic Press. 354 pp.

- Linder, S. 1987. Responses to water and nutrients in coniferous ecosystems. Pgs. 180-202. In Potentials and Limitations of Ecosystems Analysis. Ecol. Studies 61. E.D. Schulze and H.Z. Wolfer, (eds.). Springer-Verlag.
- Linder, S., M.L. Benson, B.J. Myers, and R.J. Raison. 1987. Canopy dynamics and growth of *Pinus radiata*. I. Effects of irrigation and fertilization during a drought. *Can. J. For. Res.* 17:1157-1165.
- Martin, S.W., R.L. Bailey, and E.J. Jokela. 1999. Growth and yield predictions for lower Coastal Plain slash pine plantations fertilized at mid-rotation. *South. J. Appl. For.* 23: 39-45.
- McKeand, S.E., R. Crook, and H.L. Allen. 1997. Genetic stability on predicted family responses to silvicultural treatments in loblolly pine. *South. J. Applied For.* 21:84-89.
- Murthy, R., P.M. Dougherty, S.J. Zarnoch, and H.L. Allen. 1996. Effects of elevated CO₂, nitrogen and water on net photosynthesis and foliar nitrogen concentration of loblolly pine trees. *Tree Physiology* 16:537-546.
- Piatek, K.B. and H.L. Allen. 2001. Are forest floors in mid-rotation stands of loblolly pine (*Pinus taeda* L.) a sink for nitrogen and phosphorus? *Can J. For. Res.* 31:1164-1174.
- Piatek, K.B. and H.L. Allen. 1999. Nitrogen mineralization in a pine plantation fifteen years after harvesting and site preparation. *Soil Sci. Soc. Am. J.* 63:990-998.
- Pereira, J.S., M.V. Madeira, S. Linder, T. Ericsson, M. Tomé, and M.C. Araújo. 1994. Biomass Production with Optimised Nutrition in *Eucalyptus globulus* Plantations. Pgs 13-30 In J.S. Pereira and H. Pereira (eds.), *Eucalyptus for Biomass Production*. Commission of the European Communities. 322 pp.
- Prestemon, J. P. and Robert C. Abt. 2002. Chapter 13 (TIMBR-1): Timber Products Supply and Demand. In: *The Southern Forest Assessment Final Technical Report*. General Technical Report SRS-53. USDA Forest Service, Southern Research Station, Asheville, NC.
- Pritchett, W.L. and N.B. Comerford. 1982. Long-term response to phosphorus fertilization on selected Southeastern Coastal Plain soils. *Soil Sci. Soc. Am. J.* 46:640-644.
- Sampson, D.A. and H.L. Allen. 1999. Regional influences of soil available water and climate, and leaf area index on simulated loblolly pine productivity. *For. Ecol. Manage.* 124:1-12.
- Snowdon, P. and M.L. Benson. 1992. Effects of combinations of irrigation and fertilisation on the growth and above-ground biomass production of *Pinus radiata*. *For. Ecol. Manage.* 52:87-116.
- Teskey, R.O., B.C. Bongarten, B.M. Cregg, P.M. Dougherty, and T.C. Hennessey. 1987. Physiology and genetics of tree growth response to moisture and temperature stress: An examination of the characteristics of loblolly pine (*Pinus taeda* L.). *Tree Phys.* 3:41 61.
- Vose, J.M. and H.L. Allen. 1988. Leaf area, stemwood growth and nutrient relationships in loblolly pine. *For. Sci.* 34:547 563.