MODELING THE EFFECT OF FERTILIZATION ON WOOD PROPERTIES OF LOBLOLLY PINE (*PINUS TAEDA* L.)

by

FINTO ANTONY

(Under the direction of Richard F. Daniels)

ABSTRACT

There has been an increased interest in mid-rotation application of fertilizer in loblolly pine (*Pinus taeda* L.) plantation management. However concerns have arisen about the quality of wood produced following the fertilizer application. Increment cores were collected at six height levels of thirty-two trees from a thinned, fertilized stand located on lower Coastal Plain of North Carolina. The fertilization treatments selected for this study were: 1) No Nitrogen +25lb/acre of Phosphorous 2)100lb/acre of Nitrogen + 25lb/acre Phosphorous 3) 200lb/acre of Nitrogen +25lb/acre of Phosphorous 4)300lb/acre of Nitrogen + 25lb/acre of Phosphorous. Mechanical, physical and anatomical properties were measured from pith to bark and for the three years following fertilization to examine for any significant effects of fertilization on these wood properties. A three dimensional prediction equation was developed for stiffness which explains the radial and longitudinal pattern of stiffness variation within a tree. Attempts were made to develop mathematical function for stiffness responses that occurred following fertilization.

INDEX WORDS: Loblolly pine, Fertilization, Stiffness, Intensive silviculture

MODELING THE EFFECT OF FERTILIZATION ON WOOD PROPERTIES OF LOBLOLLY PINE (*PINUS TAEDA* L.)

by

FINTO ANTONY

B. S. Forestry, The Kerala Agricultural University, India, 2001

A Thesis Submitted to the Graduate Faculty of

The University of Georgia in Partial Fulfillment

of the

Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2006

MODELING THE EFFECT OF FERTILIZATION ON WOOD PROPERTIES OF LOBLOLLY PINE (*PINUS TAEDA* L.)

by

FINTO ANTONY

Approved:

Major Professor: Richard F. Daniels

Committee: Laurence R. Schimleck

Alexander Clark, III

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
December 2006

DEDICATION

To: Dr. Richard F. Daniels

"Take up one idea. Make that one idea your life - think of it, dream of it, live on that idea. Let the brain, muscles, nerves, every part of your body, be full of that idea, and just leave every other idea alone. This is the way to success."

Swami Vivekananda

ACKNOWLEDGEMENTS

I express my deep sense of gratitude and indebtedness to Dr. Richard F. Daniels, for his constant inspiration and evaluation without which this endeavor would not have been fruitful. I am also deeply indebted to Dr. Laurie Schimleck and Mr. Alexander Clark III for their valuable advice and help given to me during the course of my study. I express my deep sense of gratitude to Dr. Dan Hall and Lewis Jordan for their valuable suggestions during the statistical analysis of the data. I thank many of my friends for their whole hearted assistance at times of great need without which this study would not have borne fruits. Finally, I would like to express my love and appreciation to my parents, Mr. Antony and Mrs. Philomina.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION AND REVIEW OF LITERATURE

INTRODUCTION

The southeastern region of the United States of America (USA), recognized as the wood basket of the world, supplies around 58% of the total wood used in the USA and 16 % of wood supplied to the world timber market (Wear and Greis 2002). Approximately, 31.3% of the total land area of the southern USA is occupied by Loblolly pine (*Pinus taeda* L.) and contributes 6.6% of the total live volume of the US forests (FIA 2002). The fast growth rate, ability to survive on a wide range of sites along with the suitability of wood for a variety of uses has made loblolly pine a key species in the USA. Loblolly pine is a principal source of raw material for the pulp and paper industry and well suited for sawn lumber and making composite wood products.

In the past, approaches to minimize per acre cost associated with plantation establishment and management led to million of acres of planted pine growing at a rate of less than 5 green tons per acre per year in the southeastern USA. Compared to other pine growing regions of the world, the current growth rate of pine in the southeastern USA is well below the original potential attainable from this region (Fox *et al*. 2006). However, various long term monitoring studies and field trials have proven that the current growth rate can be substantially increased to more than 10 green tons per acre per year by the application of appropriate silvicultural practices (Jokela *et al*. 2000, Borders and Bailey 2001).

Management practices, especially thinning and fertilization, later in the rotation are found to be biologically and financially attractive because of their ability to increase growth of mature wood close to harvest. The increase in acreage under fertilization from 200,000 acres in 1997 to more than 1.5 million acres in 2002 is an indication of potential of this practice (FNC Synthesis 2006). A long-term monitoring study established at four locations in Georgia to understand the change in growth rate of loblolly pine under varying management intensities shows that a combination of weed control and fertilizer application following intensive site preparation has the potential to increase the growth rate of loblolly pine by 270% in the Coastal Plain and 150% in the Piedmont compared to the control without weed control and fertilizer (Borders and Bailey 2001).

Even though application of fertilizer following thinning has proved to be very effective in improving growth, forest landowners and industry are concerned about the quality of wood produced following fertilization. The major objectives of this investigation are to: 1) identify the influence of fertilization on wood properties such as modulus of elasticity, ring specific gravity, microfibril angle, wall thickness, radial and tangential diameter, fiber coarseness, perimeter and specific surface, and 2) develop a method to predict these changes for making future management decisions. Before going to further details on fertilization and its impacts on growth and wood quality, an understanding of the wood properties that will be examined in this study is important.

WOOD QUALITY AND WOOD PROPERTIES

According to Gibson (1980) wood quality is "the totality of the attributes of a product which contributes to the satisfaction of needs". It is a cumulative expression of anatomical, physical and mechanical properties of a piece of wood on a particular product. Thus the definition of wood quality is complex and multifaceted, depending either on the properties of the product or on the manufacturing process. It also encompasses the ability of a product to satisfy the needs of the end user. The most important and widely used properties to express wood quality are specific gravity, microfibril angle (MFA), stiffness (modulus of elasticity, MOE) and strength (modulus of rupture, MOR).

Specific gravity describes the amount of woody material in a given volume of wood. Theoretically, it is the ratio of the density of wood with the density of water at 4^oC (Megraw 1985). Specific gravity is considered as an important wood property because of its strong correlation with the strength of wood, as well as the yield and quality of pulp produced. Specific gravity ultimately depends upon the properties of wood such as the ratio of earlywood to latewood in the annual ring, fiber wall thickness, fiber length and fiber numerical density.

Microfibril angle (MFA) is defined as the angle made by microfibrils in the S_2 layer of the cell wall with the longitudinal axis of the cell (Megraw 1985). MFA has a strong influence on stiffness, strength and dimensional stability of wood and is an important determinant of the quality of sawn timber (MacDonald and Hubert 2002). MFA decreases from pith to bark at all heights and within a ring earlywood cells possess a higher MFA compared to latewood cells (Megraw 1985). MFA varies with fiber length and cell wall thickness.

Unlike Specific gravity and MFA, MOE and MOR are the two widely accepted wood property measures in the solid wood industry. MOE describes the stiffness of a material and it is expressed as the ratio between stress and strain. MOR indicates the strength of a material defined as its load carrying capacity. Identifying and defining all these properties are essential for describing the quality of wood produced from a tree. Ultimately, these properties will decide the end use of the wood.

EFFECT OF FERTILIZATION ON GROWTH

Intensive silvicultural practices have been found to have a strong significant influence on improving site quality and the growth rate of loblolly pine. The normal growth rate of loblolly pine in the southeast USA was estimated to be 50-110 ft^3 per acre per year (Clark and Edwards 1999). However, with the proper application of intensive silvicultural practices, such as site preparation, competition control, thinning, fertilization and the use of genetically improved stock, growth rates of approximately 250-350 ft^3 per acre per year can be achieved (Borders and Bailey 2001).

Application of fertilizer in a loblolly pine management regime has been found to be one of the best ways of increasing growth rates (Schmidtling 1973, Allen 1987, Stearns-Smith *et al.* 1992). Fertilization improves the nutrient availability of soils, and provides a transient boost in growth. However, sometimes the influence of fertilizer on growth rate is unpredictable, and confounded with site characteristics, climatic conditions and the type of fertilizer used. The reported responses to fertilization were found to range from zero to 80-100 ft^3 per acre per year with respect to unfertilized stands (Allen 1987, Borders and Bailey 2001, Moorhead 1997).

EFFECT OF FERTILIZATION ON WOOD PROPERTIES

The effect of fertilization on wood properties can be explained on the basis of the quantity and quality of wood produced. The change in the quality of wood in response to fertilizer application can be expressed through various measurable characteristics, such as wood specific gravity, toughness, strength, latewood percent, tracheid length, tracheid wall thickness and MFA. It is very difficult to generalize the influence of fertilization on wood properties because of the large number of extraneous factors involved in the response. However, a mixed response in wood properties has been observed owing to fertilization as described in the following studies, which show variation with species, site characteristics and climatic conditions.

FERTILIZATION OF SOFTWOODS

One of the first studies in the southern USA to examine the effects of fertilization on slash pine (*Pinus elliotti* Engelm.) wood properties was conducted by Williams and Hamilton (1961) in the lower Coastal Plain of Georgia. They examined the effect of applying nitrogen, phosphorous, and nitrogen plus phosphorous at age 7 and reported a 26% increase in average ring width, a 6.7% decrease in specific gravity, a 2.8% decrease in percent of latewood, and no change in tracheid wall thickness from control measured on the two rings following fertilization. Similarly, an early trial (Posey 1964) in North Carolina found that nitrogen fertilizer applied as a single dose to loblolly pine at age 12 and 16 years produced a 16% reduction in specific gravity and a 12% reduction in tracheid length in the annual ring immediately following the treatment.

The age of the tree, initial specific gravity and tracheid length at the time of fertilization were reported to have an influence on the response produced. Posey (1964) found that wood properties of trees which are younger were more responsive to fertilization than older trees. In young loblolly pine, a decrease in specific gravity was observed following nitrogen fertilization (Linnartz *et al*. 1970). In younger aged trees, application of fertilizer led to decreased latewood percent and thus a reduced specific gravity, whereas at later ages the influence on latewood percent was less pronounced (Larson *et al*. 2001). In contrast, Megraw (1985) stated that the changes following fertilization do not depend upon initial specific gravity and tracheid length of trees.

Fertilizer application in combination with other silvicultural practices has been found to have a strong influence on the properties of the wood produced. A study (Clark *et al*. 2004) on the influence of annual nitrogen fertilization and vegetation control in loblolly pine revealed that annual application of nitrogen fertilizer through age 12 along with vegetation control led to a 62% increase in juvenile wood core diameter, 6 - 10% decrease in weighted stem specific gravity, and a 30 – 33% reduction in toughness compared to untreated trees. A significant drop in juvenile wood strength (9-10%) and mature wood strength (4-7%) was observed in trees receiving annual nitrogen fertilization in combination with vegetation control compared to untreated trees.

Currently, mid-rotation fertilization is receiving more interest from tree growers because of its ability to produce more mature wood without diminishing wood quality. Mid-rotation fertilization trials in radiata pine (*Pinus radiata* D.Don) with nitrogen and phosphorous (Nyakuengama *et al*. 2004) revealed that fertilization produced an increase in ring width (nitrogen 3 – 16%, phosphorous 7 – 29% and nitrogen plus phosphorous 18 – 31%), and a reduction in specific gravity (nitrogen 0%, phosphorous 3 – 7% and nitrogen plus phosphorous 7%) in rings produced following fertilizer application.

It was originally thought that changes in wood properties following fertilization was due to an increase in growth rate. A weak correlation was found between ring width and density in radiata pine after fertilization with nitrogen, phosphorous or both together (Nyakuengama *et al*. 2002). The reason proposed for the weak correlation between ring width and density was that both characteristics are under the control of widely different fiber characteristics; for example, fiber diameter influencing ring width, and fiber wall thickness controlling density.

A comprehensive description of the influence of fertilizer on wood properties is still difficult to make because the responses are highly dependent upon the site characteristics, particularly water availability and the nutrient status of the soil. Later age management studies on radiata pine (Nyakuengama *et al*. 2004) showed that the correlation between ring width and density depended on annual rainfall or seasonal rainfall, for example spring rainfall explained around 76% of the variation in correlations between growth rate and density.

The changes occurring to wood produced following fertilizer application can be resolved to a reasonable extent by explaining the variation occurring at the cellular level. Nyakuengama *et al.* (2003) examined changes in tracheid properties of radiata pine following fertilization and observed that application of nitrogen increased fiber numerical density, while reducing fiber radial diameter and wall thickness. Phosphorous increased fiber radial diameter and decreased fiber wall thickness, while nitrogen plus phosphorous caused a reduction in fiber wall thickness and increased cell radial diameter.

A fertilization study in norway spruce (*Picea abies* (L.) Karst.) found a decrease in wood density as a result of a decrease in wall thickness and an increase in radial fiber width (Lundqvist 2001). The changes in wood properties after fertilization were attributed to changes in crown characteristics, such as crown size and vigor (Megraw 1985). These changes result in increased auxin supply to the lower bole of the tree leading to increased cambial activity, and thus, production of large sized cells over a prolonged period of time.

It was found that wood properties averaged across growth rings from pith to bark did not show a significant difference owing to fertilization compared to the wood produced in rings immediately following fertilization. No variation in core specific gravity, averaged from pith to bark, was observed in loblolly pine wood due to nitrogen application (Choong *et al*. 1970, Schimidtling 1973). In radiata pine, little change was found in wood properties of whole increment cores after fertilizing with nitrogen and phosphorous (Nyakuengama *et al*. 2004). Thus, changes in wood properties averaged on a whole-tree basis after fertilization are negligible compared with the rings formed immediately after fertilizer application.

FERTILIZATION OF HARDWOODS

Similar to what was found for fertilization studies in conifers, the effect of fertilization on wood properties of plantation-grown hardwoods was variable and difficult to generalize. Some results showed no impact on wood density following nitrogen and phosphorous application to plantation grown flooded gum (*Eucalyptus grandis* (Hill) Maid.) (Hans and Burley 1972, Chauhan *et al*. 1983, Wilkins 1990), while a small increase was observed in other studies (Cromer *et al*. 1998). In mountain ash (*Eucalyptus regnans* F. Muell.) no changes to density were found due to fertilizer application (Higg and Rudman 1973).

In Tasmanian blue gum (*Eucalyptus globulus* Labill.) changes in wood properties were observed after fertilizer treatment, but the observed variation was site specific and depended on moisture availability. For example Raymond and Muneri (2000) reported an increase in basic density in rainfall-deficient sites due to addition of nitrogen and with an opposite response on wetter sites.

MODELING THE EFFECT OF FERTILIZATION

Mathematical models for predicting changes in wood properties following silvicultural practices from stump to tip and from pith to bark, would improve forest management practices. Such models would help foresters optimize their management practices and predict their wood yield and value.

Several models are available to predict silvicultural effects on wood properties of loblolly pine. One such model predicts specific gravity variation within trees from conventionally managed pine plantations (Daniels *et al*. 2002). Jordan (2001) examined MFA variation in sixty loblolly pine trees from four physiographic regions of the southeastern USA. Jordan (2001) developed prediction equations to estimate variation in MFA at any point within the tree. Clark and Daniels (2002) developed a model which estimates the variation in specific gravity of loblolly pine for different physiographic regions of southeastern USA. However, none of these models explains the variation in wood properties of loblolly pine following fertilization.

Much of the information available about fertilization and its impact on loblolly pine wood properties are conflicting. Moreover, information is lacking on the effect of fertilizer application on MFA, modulus of elasticity (MOE), modulus of rupture (MOR) and various fiber properties. The absence of a mathematical model for predicting the effect of fertilization on wood properties is a hindrance in the implementation of these practices in the field. Further studies are required to produce the information needed by practicing foresters in order to make better management decisions for producing maximum yield without sacrificing wood quality.

REFERENCES

Allen, H. L. 1987. Forest fertilizers: Nutrient amendment, stand productivity, and environmental impact. J. For. 85(2):37-46.

Borders, B. E. and R. L. Bailey. 2001. Loblolly pine-pushing the limits of growth. South. J. Appl. For. 25(2):69-74.

Chauhan, L., S. P. Agarwal, and R. Dayal. 1983. Studies on the effects of spacing and application of fertilizer on wood quality in *Eucalyptus tereticornis* Sm. Ind. For. 109: 901-905.

Choong, E. T., B. H. Box and P. J. Fogg. 1970. Wood properties of young loblolly pine in response to cultural management. LSU Forestry Note No.88. Lousiana State University. LA. 3pp.

Clark III, Alexander and R. F. Daniels. 2002. Modeling the effect of physiographic region on wood properties of loblolly pine in south eastern United States. Proceedings of fourth Workshop IUFRO S5.01.04. Canada. 54-60.

Clark III, Alexander and M. B. Edwards. 1999. Effect of six site-preparation treatments on piedmont loblolly pine wood properties at age 15. Paper presented at tenth Biennial Southern silvicultural Research Conference. 316-320.

Clark III, Alexander, B. E. Borders and R. F. Daniels. 2004. Impact of vegetation control and annual fertilization on properties of loblolly pine wood at age 12. For. Prod. J. 54(12):90-96.

Cromer, R. N., V. Baloidis, D. Cameron, C. P. Garland, S. Rance, and P. Ryan. 1998. *Eucalyptus grandis* fertilizer trials: growth, wood properties and kraft pulp yield. Appita. 51:45-49.

Daniels, R. F., H. E. Rechun, A. Clark III, and R. A. Souter, 2002. Modeling wood properties of planted loblolly pine from pith to bark and stump to tip. Proceedings of fourth Workshop IUFRO S5.01.04. Canada. 238-245.

Forest inventory and analysis-Trend data. 2002. FIA. Online document from site http:/www.fia.fs.fed.us/slides/major-trends.pdf

Forest Nutrition Cooperative Synthesis. 2006. Forest Nutrition Coopertive. An online note adapted from the site http://www.forestnutrition.org/synthesis.htm.

Fox, T. R., H. L. Allen, T. J. Albaugh, R. Rubilar and C. A. Carlson. Forest fertilization in southern pine plantations. Better Crops. 90: 12 – 15.

Gibson, E.J. 1980. Product development and quality. IUFRO Conf Div5. Oxford, England. 15 – 29.

Hans, A. S., and J. Burley. 1972. Wood quality of *Eucalyptus grandis* (Hill) Maiden in a fertilizer trial at Siamamba, Zambia. East Afr. Agric. For. J. 38:157-161.

Higgs, M. L., and P. Rudman. 1973. The effect of fertilizing and thinning on wood properties of *Eucalyptus regnans*. Appita. 27:51-55.

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.

Jordan, C. L. 2001. Modeling within-tree changes in loblolly pine microfibrilar angle in the southeast United Sates. MS thesis. University of Georgia. Georgia. 167pp.

Larson, P. R., D. E. Kretschmann, A. Clark III, and J. G. Isebrands. 2001. Formation and properties of juvenile wood in southern pines- A synopsis. General Technical Report FPL-GTR-129. Forest Product Laboratory. USDA. 42pp.

Linnartz, N. E., E. T. Choong, and P. Underwood. 1970. Diameter growth, specific gravity and tracheid length in a 4-year old loblolly pine in response to fertilizer treatment. Lousiana State Univ. Baton Rogue, Lousiana. Note 90, 4pp.

Lundqvist, S. 2001. Application of Silviscan for optimal utilization of forests in Sweden. Presentation at the Marcus Wallenberg Prize Seminar. Nationalmusuem, Stockholm.

MacDonald, E., and J. Hubert. 2002. A review of the effects of silviculture on timber quality of sitka spruce. Forestry 75(2): 107-138 pp.

Megraw, R. A. 1985. Wood quality factors in loblolly pine. TAPPI Press. Atlanta.88pp.

Moorhead, D. 1997. Forest fertilization speaker's notes. Georgia Cooperative Extension Service, College of Agricultural and Environmental Sciences, The University of Georgia, Athens, GA.

Nyakuengama, J.G., G.M. Downes, and J. Ng. 2002. Growth and wood density responses to later-age fertilizer application in *Pinus radiata*. IAWA J. 23(4): 431-448.

Nyakuengama, J. G., G. M. Downes, and J. Ng. 2003. Changes caused by mid-rotation fertilizer application to the fiber anatomy of *Pinus radiata*. IAWA J. 24(4): 397-409.

Nyakuengama, J. G., G. M. Downes, E. K. S. Nambiar, P. Blakemore and R. N. Northway. 2004. Effect of later age stand management on quality of radiate pine wood. Forest and Wood Products Research and Development Corporation. Project Report. 33pp.

Posey, C. E. 1964. The effect of fertilization upon wood properties of loblolly pine. For. Tree Improv. Program. Sch. For. North Carolina State Univ. Tech. Rep. No. 22. 61pp.

Raymond, C. A. and A. Muneri. 2000. Effect of fertilizer on wood properties of *Eucalyptus globulus*. Can. J. For. Res. 30: 136-144.

Schmidtling, R. C. 1973. Intensive culture increases growth without affecting wood quality of young southern pine. Can. J. For. Res. 3: 565-573.

Stearns-Smith, S.C., E. J. Jokela and R. C. Abt. 1992. Thinning and fertilizing southern pine stands of the lower coastal plain:-ecological and economic effect. South. J. Appl. For. 16(4):186-193.

Wear, D. N., and J. G. Greis. 2002. Southern Forest Resource Assessment: Summary of Findings. J. For. 100(7): 6-14.

Wilkins, A. P. 1990. Influence of silvicultural treatment on growth and wood density of *Eucalyptus grandis* grown on a previous pasture site. Aust. For. 53: 168-172.

Williams, R. F. and J. R. Hamilton. 1961. The effect of fertilization on four wood properties of Slash pine. J. For. 59: 662-665.

CHAPTER 2

MATERIALS AND METHODS

SITE DESCRIPTION

The study was conducted in an even aged loblolly pine plantation located at New Bern, North Carolina, that was planted in 1970. This was one of the 19 installations of the NCSFNC Region wide 13 studies established across the southeast on site-prepared loblolly pine stands during 1984-1987 (NCSFNC Report No: 39 1997). The site was located on the lower Coastal Plain of North Carolina carrying a poorly drained Leaf soil series having a site index of 69 feet (21.03 m) and basal area of 67 ft^2/acre (4.7m^2/hectare) at the time of treatment.

EXPERIMENTAL DESIGN

The experimental design was a randomized complete block with four treatments replicated four times. Blocking was done in order to reduce variation in dominant height, basal area and stem number per acre keeping the soil type similar. The treatments used in this study were: 1) Control – no Nitrogen (hereafter referred to as **000N**) 2) 100lb/acre (112Kg/ha, hereafter referred to as **100N**) 3) 200lb/acre (224Kg/ha, hereafter referred to as **200N**) 4) 300lb/acre (336Kg/ha, hereafter referred to as **300N**) with 25lb/acre (28Kg/ha) phosphorous included with each treatment. The site was thinned in 1983 and treated with fertilizer in March, 1984. All plots including **000N** were refertilized with 200lb/acre of nitrogen in 1996. The trees for the present study were harvested in 2003.

SAMPLE PREPARATION

Two trees representing the average diameter at breast height of the trees in a treatment plot were felled from each plot giving a total of 32 trees for the study. One inch (2.54 cm) thick disks were cut at six height levels (4.5 feet-1.37 m, 10 feet-3.05 m, 15 feet-4.57 m, 25 feet-7.62 m, 35 feet-10.67 m and 45 feet-13.72 m) along the stem of these trees. Radial sections from pith to bark of ½ inch X ½ inch (1.27 cm X 1.27 cm) were cut from these disks, oven dried to a moisture content of 8% and glued into core holders. Thin radial strips of thickness approximately 0.0629 inch (1.6 mm) were cut from these sections using a twin-blade circular saw at the wood property lab of United States Department of Agriculture-Forest Service (USDA-FS), Athens, Georgia.

From each felled tree, three 2-feet (0.61 m) bolts were also cut at 8 feet (2.44 m), 24 feet (7.32 m) and 40 feet (12.19 m) representing the mid point of 16-feet (4.88 m) saw logs. Static bending samples of dimension 1 inch X 1 inch X 16 inch (2.54 cm X 2.54 cm X 40.64 cm) were cut starting at the 1984 annual ring. Samples of size 1 inch X 1 inch X 1 inch (2.54 cm X 2.54 cm X 2.54 cm) were cut from one end of the static bending samples and sent to CSIRO Forestry and Forest Products (Australia) for SilviScan analysis. From these blocks, radial strips of 2 mm (0.08 inch) (tangentially) X 7 mm (0.28 inch) (longitudinally) X 25 mm (0.98 inch) (radially) were cut and analyzed by SilviScan, which measured air-dry density at an interval of 25 μm using X-ray densitometry (Evans 1994) and MFA at an interval of 1 mm using X-ray diffractometry (Evans 1997). SilviScan calculated an estimate of stiffness from the air dry density and X-ray diffraction pattern at a resolution of 1 mm (Evans 2003). The image analysis system of SilviScan (Evans 1994) was used to estimate the fiber dimensions, radial and tangential diameter at an interval of 25 μm. Other fiber properties such as tracheid wall thickness, coarseness, specific surface and perimeter were determined at an interval of 25 μm from the relationships of these properties with air dry density and radial and tangential wall thickness (Evans 1994).

REFERENCES

NCSFNC Report No. 39. 1997. North Carolina Forest Nutrition Cooperative. Department of Forestry. North Carolina State University. Raleigh, NC.

Evans, R. 1994. Rapid measurement of the transverse dimensions of tracheids in radial wood sections from Pinus radiata. Holzforschung 48: 168-172.

Evans, R. 1997. Rapid scanning of microfibril angle in increment cores by x ray diffractometry. In Microfibril Angle in Wood. Proceedings of the IAWA / IUFRO International Workshop on the Significance of Microfibril Angle to Wood Quality, Nov. 1997, Westport, New Zealand. Edited by B.G. Butterfield, University of Canterbury Press, pp. 116-139.

Evans, R. 2003. Wood stiffness by X-ray diffractometry. In Proceeding of Workshop on the Characterization of the Cellulosic Cell Wall, Aug. 2003, Grand Lake, Colorado. Edited by D. D. Stokke and L.H. Groom, Blackwell Publishing, pp. 138-146.

CHAPTER 3

EFFECT OF MID-ROTATION FERTILIZATION ON MECHANICAL, PHYSICAL AND ANATOMICAL PROPERTIES OF LOBLOLLY PINE (*PINUS TAEDA* L.)

ABSTRACT

Mechanical, physical and anatomical properties of wood were measured for cores collected at six height levels from a thinned, fertilized mid-rotation loblolly pine (*Pinus taeda* L.) plantation located at New Bern, North Carolina. The study was a randomized complete block design receiving four levels of nitrogen fertilizer (Control- no fertilizer, 100lb/acre, 200lb/acre and 300lb/acre along with 25lb/acre of phosphorous with each treatment), each replicated in four randomized complete blocks. Statistically significant differences among treatments were absent for basal area weighted ring specific gravity, latewood specific gravity, percent latewood and earlywood specific gravity averaged across annual rings from pith to bark. A significant response was observed for a three-year weighted average taken following nitrogen fertilization on MOE, ring specific gravity, latewood specific gravity, percent latewood, radial diameter, and perimeter for the treatment 300lb/acre. Decreases in MOE (1.13 GPa), ring specific gravity (0.03), latewood specific gravity (0.03), percent latewood (5%), wall thickness (0.16 μm) and increases in MFA (2.07^{o}), radial diameter (1.53 μm), and perimeter (4.39 μm) were observed from control treatments for trees received 300lb/acre of nitrogen. Properties such as earlywood specific gravity, tangential diameter, coarseness and specific surface showed little change following fertilizer application. Wood properties of trees that received lower levels of nitrogen fertilizer (100lb/acre and 200lb/acre) were not affected following treatment. There was no height related trend in wood property changes due to nitrogen application. A time and height dependent change following treatment in ring specific gravity, latewood specific gravity, percent latewood and earlywood specific gravity was evident from the repeated measure analysis for five-year ring averages taken following treatment, but none of the treatments showed significant differences following fertilization. Even though a significant difference was absent for different wood properties following fertilization, the rings produced immediately after fertilization showed a response particularly for trees receiving 300lb/acre of nitrogen. In summary, fertilization did not produce a significant change in wood properties of whole-cores taken at six height levels; however there is a decline in wood quality immediately after fertilization, which depends upon the amount of fertilizer applied irrespective of height.

Key words: wood properties, wood quality, forest fertilization, loblolly pine, stiffness

INTRODUCTION

Mid-rotation fertilization is a widely accepted silvicultural practice in loblolly pine (*Pinus taeda* L.) plantations throughout the southeastern United States of America (USA). Since 1996, when 200,000 acres were fertilized, there has been a five fold increase in the annual area fertilized with 1.5 million acres fertilized in 2002 (FNC Synthesis 2006). This was attributed to the capacity of mid-rotation fertilization to maximize wood production in biologically (FNC Synthesis 2006) and financially attractive ways (Borders and Bailey 2001).

Fertilization at mid-rotation in loblolly pine stands has been found to have a strong positive influence on volume production. Data from various field trials established by the North Carolina State Forest Nutrition Cooperative (NCSFNC) point out that over 85 percent of fertilized stands responded to a combination of nitrogen (N) and phosphorous (P) fertilization (one-time application of 200 lbs/acre N and 25 lbs/acre P) with an average growth gain of 30% over a six-year period (FNC Synthesis 2006). A long term monitoring study across a wide range of sites in Georgia (Borders and Bailey 2001) revealed that intensive practices such as vegetation control combined with annual fertilization for plantation loblolly pine can produce a mean annual increment of 325 to 490 ft^3/acre/year by age of 10-12 years which is a 1.5 to 3.5 fold increase in annual increment compared to untreated control plots. In addition, growth and yield models prepared from fertilized mid-rotation loblolly pine plantations support these conclusions (Amateis *et al.* 2000).

The quality of wood, in terms of its mechanical, physical and anatomical properties, produced from fertilized loblolly pine plantations has raised concerns in the forestry community. Large scale studies installed to determine the effect of fertilization on growth in the USA and have been used to determine the effect of mid-rotation fertilization on wood properties. The wood properties examined include ring specific gravity, latewood specific gravity and earlywood specific gravity, percent latewood, microfibril angle, modulus of elasticity etc. Of these, specific gravity is considered as a key wood property because of its strong correlation with strength and stiffness of solid wood products and the yield and quality of pulp produced (Nyakuengama 1991, Morling 2002). Compared to other wood properties specific gravity can be measured easily and is expressed as the amount of woody material (cellulose + lignin + hemicellulose) in a given volume of wood.

In conifers, the effect of early age nitrogen fertilization (1st and 4th year after establishment at a rate of 14 lb/acre and 72 lb/acre) on whole core specific gravity was reported to be not significant (Choong *et al.* 1970). However, growth rings produced immediately following fertilization show a decrease in specific gravity (Williams and Hamilton 1961, Zobel *et al.* 1961, Mallonee 1975, Morling 2002). The reduction in density was found to last for a variable period of time (reported 2-5 years) after fertilizer application and then revert back to a pattern similar to unfertilized trees (Morling 2002, Nyakuengama *et al.* 2002). A similar pattern of decrease was also observed for specific gravity of latewood following annual fertilization (Clark *et al.* 2004) in 12-year-old loblolly pine. However, there was no specific pattern of change in earlywood specific gravity owing to fertilization.

Percent latewood is defined as the proportion of latewood in an annual ring and considered as an important index in describing wood strength and quality. Percent latewood is the major determinant of variation in wood specific gravity (Bamber and Burley 1983). A reduction in percent of latewood for a few years (two to three) following fertilization was observed, similar to ring specific gravity (Williams and Hamilton 1981, Clark *et al.* 2004).

Microfibril angle (MFA) is the angle made by the cellulose microfibrils in the S2 layer of the cell wall relative to the axis of the cell (Barnett and Bonham 2004). In general, MFA decreases from pith to bark at all height levels in loblolly pine (Megraw 1985). The general trend of decreasing MFA, from pith to bark, may be interrupted by changes in growth rate caused by various climatic and silvicultural practices. Earlier studies observed a slight increase (2-3 ^{O}) in Douglas fir (Erickson and Arima 1974) and radiata pine (Downes *et al.* 2002), following thinning and fertilization, returning to normal a few years after the treatment. However, the number of studies evaluating the effect of fertilization on MFA is limited in practice because of the high cost associated with measuring MFA. It was observed that other fiber anatomical properties such as fiber radial diameter, tangential diameter and wall thickness are subject to change following fertilization. In radiata pine, Nyakuengama *et al*. (2003) observed a decrease of 0.33 μm in 7-year average fiber radial diameter following 178-200 lb/acre of nitrogen application compared to the control where no fertilizer was applied (32.35 μm), where as application of phosphorous (70-90 lb/acre) and nitrogen plus phosphorous increased radial diameter by 0.87 μm and 0.58 μm compared to the control. All combinations of nitrogen and phosphorous fertilizer application decreased wall thickness (nitrogen 3.21 μm, phosphorous 3.18 μm and nitrogen plus phosphorous 3.09 μm) compared to that of the control (3.28 μm). However changes to tangential diameter following fertilization were observed to be negligible (0-0.35 μm) compared to the control (29.30 μm).

Modulus of elasticity (MOE), a measure of wood deformation under an applied load, is a property of particular interest to the lumber industry. In loblolly pine, MOE follows an increasing trend from pith to bark at all height levels similar to ring specific gravity (Megraw *et al.* 1999), which was explained by the variation in specific gravity (Larson *et al.* 2001) and microfibril angle (Cave and Walker 1994). A study conducted on radiata pine at two different sites in Australia found a 12% decrease in MOE in boards cut from the fertilized region of logs at one site, but no difference was found at the second site (Nyakuengama *et al.* 2004).

In the last 20 years, mid-rotation fertilization following thinning has been widely accepted in loblolly pine plantation management. Based on the above research findings, under the perspective of gain in yield and volume growth, these practices are promising. However, the quality issues of wood produced from fast grown plantations is still a matter of debate. The objective of the present study is to look at the changes in mechanical, physical and anatomical properties of loblolly pine wood produced from pith to bark and at six height levels in response to mid-rotation application of four different levels of nitrogen fertilizer.

MATERIALS AND METHODS

DATA COLLECTION

Ring specific gravity (RSG), latewood specific gravity (LWSG), early wood specific gravity (EWSG) and percent of latewood (LWP) were determined by scanning pith to bark radial strips cut from 1-inch thick disks using an X-ray densitometer (Quintek Measurement System™) with a resolution of 0.0024 inch (0.06 mm). A specific gravity value of 0.480 was used to distinguish the transition from earlywood to latewood. Weighted whole core average and a three-year average of ring specific gravity (WSG), latewood specific gravity (WLG), earlywood specific gravity (WEG) and percent latewood (WLP) based on the ring basal area were calculated as:

$$\mathrm{WSG} = \left(\sum \Pi \left(r_i^2 - r_{i-1}^2 \right) \rho_i \right) / \Pi r_n^2 \qquad \textbf{(1)}$$

Where r_i is the radius of ith ring and ρ_i is the ring specific gravity of ith ring (Hoag and Kramer 1991).

Near infrared (NIR) reflectance spectra were collected from the radial face of all SilviScan strips at an interval of 0.1968 inch (5 mm) using a NIRSystems Inc. Model 5000 scanning spectrophotometer. NIR spectra were also collected at an interval of 5 mm for the three rings following fertilization from the radial face of the X-ray densitometry strips cut from the 1 – inch thick disks. All NIR spectra were collected in a light proof environment to avoid any intervention of stray light on NIR measurements. A 5 mm X 5 mm mask was used to ensure a constant area was tested. The SilviScan data and NIR spectra collected from the SilviScan strips using the NIR Systems 5000 scanning spectrophotometer were used to develop Partial Least

Square (PLS) regression calibrations for predicting air-dry density, MFA, stiffness and fiber properties from the NIR spectra collected from the fertilized region (three rings following fertilization) of the pith to bark radial strips at six height levels. The calibrations were developed using Unscrambler Software (Version 9.2). Basal area weighted averages of these properties were calculated using the equation (1).

DATA ANALYSIS

An analysis of variance (ANOVA) was conducted on WSG, WLG, WEG and WLP values averaged from pith to bark and the three-year average following fertilization to examine any significant changes to the wood properties owing to the different levels of fertilization. The full linear mixed model used for the analysis is represented as:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_l + (\alpha\beta)_{ij} + (\alpha\gamma)_{il} + (\beta\gamma)_{jl} + T_{ijk} + \varepsilon_{ijkl} \quad \textbf{(2)}$$

$$i = 1,\dots,M,\ j = 1,\dots,M_i,\ k = 1,\dots,M_{ij},\ l = 1,\dots,n_{ijk}$$

Where,

y_{ijkl} = property value of the l^{th} height level, of the k^{th} tree, of the j^{th} block, receiving i^{th} treatment,

μ = the population mean,

α_i = the i^{th} treatment effect,

β_j = the j^{th} block effect with $\beta_j \overset{iid}{\sim} N(0, \sigma^2_\beta)$,

γ_l = the l^{th} height level effect,

$(\alpha\beta)_{ij}$ =the interaction of the i^{th} treatment and j^{th} block effects with $(\alpha\beta)_{ij} \overset{iid}{\sim} N(0, \sigma^2_{\alpha\beta})$,

$(\alpha\gamma)_{il}$ =the interaction of the i^{th} treatment and l^{th} height level effect,

$(\beta\gamma)_{jl}$ = the interaction of the j^{th} block and l^{th} height level effect with $(\beta\gamma)_{jl} \overset{iid}{\sim} N\left(0, \sigma^2_{\beta\gamma}\right)$,

T_{ijk} = the effect of the k^{th} tree of the j^{th} block receiving i^{th} treatment with $T_{ijk} \overset{iid}{\sim} N\left(0, \sigma^2_T\right)$,

ε_{ijkl} = residual error, with $e_{ijkl} \overset{iid}{\sim} N\left(0, \sigma^2 \mathbf{I}_{ijk}\right)$

The first step was to fit Eq.(2) with different combinations of random effects in the full model. The random effects (block, block*treatment, block*height and individual tree effect) which provided the best fit to Eq. (2) based on Akaike's Information Criteria (AIC) and Bayesian Information Criteria (BIC, lower AIC and BIC is better) remained in the model, others were dropped from the full model. Since the measurements were taken at approximately equally spaced height intervals within the tree, we can expect existence of a correlation among measurements taken at different height levels. The next step was to revise Eq. (2) to include selected random terms with proper spatial correlation structure. Spatial structures tried includes: Gaussian, Log linear, Power, Exponential and Linear models. The best spatial structure was selected based on the improvement it made on the model fitness criteria (AIC and BIC). Selected random term effects and correlation for each wood property are provided in appendix A. Multiple comparisons of least square means were conducted using Tukey-Kramer tests where the fixed effects in the model were found to be significant. The above method was also used for the analysis of the weighted three-ring average of MOE, MFA and fiber property values predicted from the NIR spectra. Selected random effect and correlation structure for each wood property are given in appendix B.

A repeated measure ANCOVA was used to analyze the time and height dependent change in RSG, LWSG, EWSG and LWP values of five rings following fertilization. The full linear mixed model used for the analysis was represented as:

$$Y_{ijklm} = \mu + Y_{83} + \alpha_i + \beta_j + \gamma_l + A_m + (\alpha\beta)_{ij} + (\alpha\gamma)_{il} + (\alpha A)_{im} + (\gamma A)_{lm} + (\alpha\gamma A)_{ilm} + T_{ijk} + \varepsilon_{ijklm} \quad \textbf{(3)}$$

$$i = 1,\ldots,M,\ j = 1,\ldots,M_i,\ k = 1,\ldots,M_{ij},\ l = 1,\ldots,M_{ijk},\ m = 1,\ldots,n_{ijkl}$$

Where,

Y_{ijklm} = property value at m^{th} year of the l^{th} height level, of the k^{th} tree, of the j^{th} block, receiving i^{th} treatment,

μ = the population mean,

Y_{83} = property value at year 1983 as a covariate,

α_i = the i^{th} treatment effect,

β_j = the j^{th} block effect with $\beta_j \overset{iid}{\sim} N\left(0, \sigma^2_\beta\right)$,

γ_l = the l^{th} height level effect,

A_m = the m^{th} year level effect,

$(\alpha\beta)_{ij}$ = the interaction of the i^{th} treatment and j^{th} block effects with $(\alpha\beta)_{ij} \overset{iid}{\sim} N\left(0, \sigma^2_{\alpha\beta}\right)$,

$(\alpha\gamma)_{il}$ = the interaction of the i^{th} treatment and l^{th} height level effect,

$(\alpha A)_{im}$ = the interaction of the i^{th} treatment and m^{th} year level effect,

$(\gamma A)_{lm}$ = the interaction of the l^{th} height and m^{th} year level effect,

$(\alpha\gamma A)_{ilm}$ = the interaction of the i^{th} treatment, l^{th} height and m^{th} year level effect,

T_{ijk} = the effect of the k^{th} tree of the j^{th} block receiving i^{th} treatment, with $T_{ijk} \overset{iid}{\sim} N\left(0, \sigma^2_T\right)$

ε_{ijklm} = residual error, with $e_{ijkl} \overset{iid}{\sim} N\left(0, \sigma^2 \mathbf{I}_{ijk}\right)$

The first step was to fix the random effects in Eq.(3) based on the AIC and BIC values. The model which gave the best fit criteria was selected for further analysis. Each measurement was taken at equally spaced time intervals from year 1984 to year 1988 at approximately equally spaced height intervals within the same tree. We can expect a horizontal correlation among individual observations taken across time and a vertical correlation among observations taken within a year across heights. The horizontal correlation from time to time was accounted by incorporating an 'Autoregressive type (1)' correlation structure in to Eq. (3) for all properties. The vertical correlation among height intervals was accounted for by incorporating a 'Power' spatial correlation structure in to the model for all properties. Both these correlation structures were selected based on the improvement made by the different combination of time and spatial correlation structures in AIC and BIC criteria. Multiple comparisons of least square means were conducted using Tukey-Kramer test where the terms in the model were found to be significant.

The analysis of variance was conducted using the MIXED procedure available in SAS version 9.1 (SAS 2004).

RESULTS

ANALYSIS OF WHOLE-CORE WEIGHTED AVERAGES

The main effect of fertilizer treatment was not significant for WSG averaged from pith to bark. The effect of height was found to be significant at the 0.05 level ($P<0.0001$) and the interaction between height and treatment was significant at the 0.1 level ($P=0.0998$) (Table 3.1). Even though no significant treatment difference exists, an increase was observed for 100N (0.4714) and 200N (0.4708) compared to control (0.4569) and a decrease for 300N (0.4490) in average WSG (Table 3.2). The significant interaction between treatments with height can be attributed to a large variation in specific gravity from stump to tip of the tree (a decrease from 0.5163 at breast height to 0.4226 at 45 feet) (Table 3.3).

The factor height was significant for WLG at the 0.05 level (P=0.0003) (Table 3.1). The treatments effects were found not to be significant. However, a significant difference exists in the average WLG of treatments 100N (0.7184) and 300N (0.6955). The WLG of treatment 100N (0.7184) showed an increase from the control (0.7025), but that of 200N (0.7061) remained the same and a decrease was observed for 300N (0.6955) from the control (Table 3.2). Across height levels the variation was small and showed a change from 0.7111 at 4.5 feet, 0.7218 at 10 feet, 0.7118 at 15 feet, 0.7074 at 25 feet, 0.6999 at 35 feet and 0.6818 at 45 feet (Table 3.3).

The main effect height (P<0.0001) was found to be significant at the 0.05 level (Table 3.1). The WLP of treatments 100N (40.69%), 200N (40.04%) was increased compared to control (38.42%) while that of 300N (37.96%) decreased (Table 3.2). The variation of average WLP across height was found to be high with 50.39% at 4.5 feet, decreasing to 31.55% at 45 feet (Table 3.3).

The main effect of height (P=0.0009) was highly significant for average WEG (Table 3.1). The difference among treatments was small (Control = 0.3034, 100N = 0.3020, 200N = 0.3130 and 300N = 0.2972) (Table 3.2). The WEG decreased from 4.5 feet (0.3188) up to 15 feet (0.2969) and then started increasing from 25 feet (0.2984) to 45 feet (0.3040) (Table 3.3).

ANALYSIS OF THREE-YEAR POST FERTILIZATION AVERAGES

Average basal area weighted MOE for the three years following fertilization varied significantly among the fertilizer treatments (P=0.0324) and height (P<0.0001) (Table 3.4). Comparison of treatments revealed that the MOE of treatment 300N (10.27 GPa) was significantly lower than the treatment 100N (11.99 GPa) (Table 3.5). Even though other treatment comparisons did not show any difference, the MOE of 100N (11.99 GPa) increased slightly compared to the control (11.40 GPa) and that of 200N (10.74 GPa) was less than the control. The height to height variation was highly significant with a decrease in average MOE from the bottom to top of the tree (13.65 GPa at 4.5 feet, 13.32 GPa at 10 feet, 13.18 GPa at 15 feet, 10.92 GPa at 25 feet, 8.91 GPa at 35 feet and 6.61 GPa at 45 feet) (Table 3.6).

The main effects of treatment (P=0.0209) and height (P<0.0001) were found to be significant for the three-year basal area weighted average of RSG following fertilization (Table 3.4). The treatments 000N (0.4422), 100N (0.4525) and 200N (0.4464) differed from 300N (0.4116) at the 0.05 level (Table 3.5). The specific gravity of 100N and 200N increased and those of 300N decreased compared to the control (0.4422). The highly significant height term was mainly caused by large variation in specific gravity across different height levels (decrease from 0.5287 at 4.5 feet to 0.3730 at 45 feet) (Table 3.6).

Treatment (P<0.0001) and height (P<0.0001) were significant at the 0.05 level for three-year average WLG (Table 3.4). The average WLG of 300N (0.6379) significantly decreased from 000N (0.6738) (Table 3.5). The WLG of 100N (0.6912) and 200N (0.6580) showed a significant difference from 300N (0.6379). The variation across height level was large enough to show significant differences among height levels (0.7018 at 4.5 feet, 0.7018 at 10 feet, 0.6988 at 15 feet, 0.6743 at 25 feet, 0.6487 at 35 feet and 0.5658 at 45 feet) (Table 3.6).

The effect of fertilization treatment was significant (P=0.0365) with the WLP of 100N (36.44%) and 200N (37.72%) showing a significant difference from 300N (29.18%). Both 100N and 200N showed a considerable increase in latewood proportion compared to 000N (34.55%) (Table 3.5). The significant height term (P<0.0001) (Table 3.4) indicates large variation in average WLP across height level in a tree (54.93% at 4.5 feet, 44.88% at 10 feet, 39.91% at 15 feet, 29.53% at 25 feet, 20.53% at 35 feet and 15.56% at 45 feet) (Table 3.6). It was found that the WLP of lower heights were significantly different from that of upper heights. The presence of a significant interaction between treatment and height (P=0.0335) was observed for WLP. However, this treatment by height interaction mainly attributed to the large variation in WLP from height to height.

WEG varied statistically from height to height (P<0.0001) (Table 3.4). However, variation in WEG across heights was less (0.3172 at 4.5 feet, 0.3013 at 10 feet, 0.2933 at 15 feet, 0.2989 at 25 feet, 0.3099 at 35 feet, and 0.3416 at 45 feet) than WSG, WLP and WLG (Table 3.5). The effect of fertilization treatment was not significant, but the 200N treatment (0.3199) showed an increase in WEG from the control (0.3093) and that of 100N (0.3062) and 300N (0.3061) showed a slight decrease from the control (Table 3.6).

For three-year average MFA, the height to height variation (P<0.0001) was the only significant term in the model (Table 3.4). This was attributed to the variation in MFA at different height levels. It was found that MFA was higher at 4.5 feet (21.40^o) and decreased to 16.68^o at 10 feet and 14.71^o at 15 feet. MFA then increased to 16.46^o at 25 feet, 20.56^o at 35 feet and reached a maximum of 27.68^o at 45 feet (Table 3.6). The effect of fertilization treatment was not found to be significant, but MFA of treatments 200N (20.60^o) and 300N (20.73^o) were greater than the control (18.66^o) while that of treatment 100N (18.34^o) showed little change from the control (Table 3.5).

The large variation in average cell wall thickness across height levels led to a highly significant height term (P<0.0001) (Table 3.4). It was found that wall thickness decreased from the base to the top of the tree (4.16 μm at 4.5 feet, 3.84 μm at 10 feet, 3.65 μm at 15 feet, 3.25

μm at 25 feet, 2.91 μm at 35 feet and 2.71 μm at 45 feet) (Table 3.6). The effect of fertilization treatment was not significant and it was observed that the variation in cell wall thickness owing to fertilizer application was small (Control = 3.43 μm, 100N = 3.50 μm, 200N = 3.48 μm, 300N = 3.27 μm) with a small decrease for treatment 300N (Table 3.5).

The effects of fertilizer treatment (P=0.0253) and height (P<0.0001) were found significant for three year average of cell radial diameter (Table 3.4). The radial diameter of treatment 300N (38.46 μm) was significantly greater than that of the control (36.93 μm) and the 200N (36.86 μm) at the 0.05 level and the 100N (37.03 μm) at the 0.1 level (Table 3.5). The significant height to height variation can be attributed to the increase in radial diameter from bottom to top of the tree (34.14 μm at 4.5 feet, 36.41 μm at 10 feet, 36.78 μm at 15 feet, 37.98 μm at 25 feet, 37.95 μm at 35 feet and 40.67 μm at 45 feet) (Table 3.6).

The height term was highly significant (P<0.0001) for cell tangential diameter (Table 3.4) and it was found that tangential diameter increased from the bottom to the top of the tree (32.40 μm at 4.5 feet, 33.10 μm at 10 feet, 32.99 μm at 15 feet, 33.25 μm at 25 feet, 33.20 μm at 35 feet and 35.80 μm at 45 feet) (Table 3.6). A change in tangential diameter was not observed for different treatments: 33.18 μm for control, 33.61 μm for 100N, 33.16 μm for 200N and 33.87 μm for 300N (Table 3.5).

Fiber coarseness varied significantly from height to height (P<0.0001) (Table 3.4). Fiber coarseness decreased from the bottom to the top of the tree (626.61 μg/m at 4.5 feet, 630.74 μg/m at 10 feet, 598.91 μg/m at 15 feet, 549.19 μg/m at 25 feet, 486.43 μg/m at 35 feet and 471.14 μg/m at 45 feet) (Table 3.6). The difference across fertilizer treatments was not significant. Coarseness was greatest for treatments 100N (569.69 μg/m) and 200N (565.96 μg/m) compared to the control (557.31 μg/m) and was least for treatment 300N (549.05 μg/m) (Table 3.5).

The fertilizer treatment effect was found to be significant (P=0.0315) for three year average perimeter following fertilization (Table 3.4). It was found that the perimeter of treatment 300N (144.80 μm) was significantly greater than the control (140.41 μm) and 200N (140.22 μm) at the 0.05 level. The perimeter of treatment 100N (141.53 μm) and 200N showed little change compared to the control (Table 3.5). The significant height effect (P<0.0001) was mainly due to the large variation from bottom to the top of the tree (133.26 μm at 4.5 feet, 139.46 μm at 10 feet, 139.80 μm at 15 feet, 142.71 μm at 25 feet, 142.60 μm at 35 feet and 152.60 μm at 45 feet) (Table 3.6).

Three year average specific surface varied significantly by height (P<0.0001) (Table 3.4), due to the large increase in perimeter from the lower height levels to the upper height levels (223.26 m^2/kg at 4.5 feet, 243.59 m^2/kg at 10 feet, 257.25 m^2/kg at 15 feet, 283.69 m^2/kg at 25 feet, 315.78 m^2/kg at 35 feet and 379.30 m^2/kg at 45 feet) (Table 3.6). The specific surface of treatment 300N (295.80 m^2/kg) was greater than that of the control (283.20 m^2/kg), where as those of 100N (275.59 m^2/kg) and 200N (280.65 m^2/kg) were less than the control (Table 3.5).

REPEATED MEASURE ANALYSIS

Repeated measure analysis of ring specific gravity averaged over six heights and five years following fertilizer application indicates lack of treatment effect on RSG. Trends of ring specific gravity over time (P<0.0001) and height (P<0.0001) were found to be highly significant (Table 3.7). The significant interaction of treatment with height (P=0.0148) and with year (P=0.0179) along with significant three factor interaction among treatment, height and year

(P<0.0001) indicates the presence of time and height dependent changes in treatment effect on RSG taken at five years following fertilization (Table 3.8, Figure 3.1).

LWSG averaged over six heights and five years following fertilization showed a significant fertilizer treatment effect (P=0.0147) (Table 3.7). The overall average LWSG of 100N (0.6896) was found to be significantly higher than 300N (0.6498), where as those of 200N (0.6703) and 000N (0.6771) were similar. The significant two way interaction of treatment with year (P=0.0356) indicates a horizontal trend in LWSG change for five years following fertilization. This was mainly attributed to the year to year variation in LWSG from 1984 to 1988 (Table 3.9, Figure 3.2) rather than the influence of any treatment effect. A height and time related change for treatment effect (three way interaction among treatment, height and year) on LWSG was absent.

The three way interaction among fertilizer treatments, height and year was significant for LWP (P<0.0001) (Table 3.7). There were also significant interactions of fertilizer treatment with height (P<0.0001) and with year (P<0.0001) and the significant main effects of height (P<0.0001) and year (P<0.0001). The significant interaction of treatment with height is attributed to the highly significant variation in LWP from stump to tip of the tree and from year 1984 to 1988 (Table 3.10, Figure 3.3).

The main effect of fertilizer treatment on five year average EWSG across six heights was found to be significant (P=0.0007) (Table 3.7). It was found that the overall average EWSG of treatment 200N (0.3155) was greater than all other treatments (000N = 0.3075, 100N = 0.3030, 300N = 0.2932). Earlywood specific gravity showed a highly significant interaction among factors treatment, height and year (P<0.0001). There were significant interactions between fertilizer treatment and height (P<0.0001) and between treatment and year (P<0.0001) along with the main effect terms height (P<0.0001), and year (P<0.0001) indicate that the major contributors of three-way interaction are variation due to height and growth year (Table 3.11, Figure 3.4).

DISCUSSION

Results from the present investigation showed that application of different levels of nitrogen fertilizer (no nitrogen, 100lb/acre, 200lb/acre and 300lb/acre) along with 25lb/acre phosphorous did not produce a significant difference in WSG averaged from pith to bark for cores taken at six height levels. This supports the earlier findings of fertilizer application on cores taken at breast height (Mora 2003, Megraw 1985, Choong *et al.*. 1970). WLG, WLP and WEG are major contributors to ring specific gravity, and the weighted average from pith to bark was not significantly different at six height levels of the tree after fertilization at mid-rotation. Even though the effect of treatment was not statistically significant on whole core weighted average of these four wood properties, lower values of WSG, WLG and WLP were observed for treatment 300N from 000N, while WEG remained relatively constant for all treatments (Table 3.2). The WSG, WLG and WLP of treatment 100N and 200N were similar to 000N. However, it is not possible to attribute these changes in whole core average values conclusively to fertilizer applied at 1984 since numerous silvicultural, edaphic and climatic factors are involved in the growth of tree.

The effect of fertilizer application on wood properties was considered to be transient in nature and may last for a few years following fertilization (Posey 1964, Ross *et al.* 1979). The changes to wood properties due to mid-rotation nitrogen application could possibly be explained on the basis of averages taken over a short time period following fertilization rather than on averaged values taken across annual rings from pith to bark. The lower value in three-year average stiffness and WSG for treatment 300N from control treatments denotes the formation of a weak band of wood following fertilization (Table 3.5). This change in MOE and WSG might be attributed to the cumulative effect of changes in other properties such as a lower LWSG, LWP, wall thickness and greater MFA, radial diameter and perimeter in the period immediately following fertilizer application (Table 3.5). A significant difference in three-year weighted average fiber properties such as wall thickness, radial diameter and perimeter confirms this hypothesis.

The effect on wood properties following fertilization depends upon the amount of fertilizer applied. Lower values in three-year MOE, WSG, WLG, WLP, wall thickness and greater MFA, fiber radial diameter and perimeter were observed for treatment 300N. However, the three-year weighted average wood properties of treatments 100N and 200N showed little variation from the control (Table 3.5). The time required for wood properties to revert back to normal varies with the amount of fertilizer applied which was clear from the plots of ring by ring values of RSG, LWSG and WLP (Figure 3.1, 3.2 and 3.3). RSG of the 300N treatment falls to values well below the other treatments and took about three years to return to normal (Figure 3.1). Differences in LWSG were also pronounced in trees receiving 300N, which showed a lower value for one or two years at all heights following treatment and then recovered with LWSG similar to the control (Figure 3.2). This short decrease in LWSG might be due to reduced secondary wall thickening of latewood tracheids following fertilization (Clark *et al.* 2004). This temporary change in specific gravity was attributed to large responses in the crown (especially needle formation) and hence a temporary change in wood formation with higher earlywood to latewood ratio (Larson *et al.* 2001).

Limited studies have examined the effect of fertilization on wood properties at different heights. Mallonee (1975) found that treatments have less influence at upper height levels. Most of the wood properties follow some type of trend with height level such as a decrease for MOE and RSG and an increase in MFA as tree height is increased. In the present investigation the treatment by height interactions were not significant for weighted whole core and three-year average of most of the wood properties. This confirms a lack of height dependent differences in the effect of fertilizer treatment on wood properties averaged across the three years following fertilization. However, the significant interaction of treatment with height in repeated measure analysis of five year non-weighted RSG, LWP and EWSG was attributed to the large variation in these wood properties from height to height.

To conclude, differences were absent in weighted averages of WSG, WLG, WEG, WLP taken across annual rings from pith to bark owing to application of different levels of nitrogen fertilizer at six height levels in a mid-rotation loblolly pine plantation. A significant change was observed for three year weighted average MOE, WSG, WLG, WLP, fiber radial diameter and perimeter following fertilization. Application of lower levels of fertilizer (100lb/acre and 200lb/acre) showed a positive effect on wood properties because of increased growth in mature wood with little negative effect on wood properties. However, 300N resulted in a decline in three-year averages of MOE, WSG, MFA and other fiber properties such as wall thickness, radial diameter and fiber perimeter. So a proper selection of mid-rotation fertilization practice must be made by taking account of two factors: the gain in yield and the reduction in the quality of wood produced. In view of the results reported here mid-rotation nitrogen fertilization, at a rate of 100lb/acre and 200lb/acre, has little influence on the quality of wood produced at the post fertilization.

REFERENCES

Amateis, R. L., J. Liu, M. J. Ducey and H. L. Allen. 2000. Modeling response to mid-rotation Nitrogen and Phosphorous fertilization in loblolly pine plantations. South. J. Appl. For. 24: 207 – 212.

Bamber, R. K. and J. Burley. 1983. The wood properties of radiate pine. Commonwealth Agricultural Bureau. London.

Barnett, J. R. and V. A. Bonham. 2004. Cellulose microfibril angle in the cell wall of wood fibers. Biol. Rev. 79: 461-472.

Borders, B. E. and R. L. Bailey. 2001. Loblolly pine- pushing the limits of growth. South. J. Appl. For. 25: 69 – 74.

Cave, I. D. and J.C.F. Walker. 1994. Stiffness of wood in fast grown plantation softwoods: the influence of microfibril angle. For. Prod. Jour. 44: 43-48

Choong, E. T., B. H. Box and P. J. Fogg. 1970. Wood properties of young loblolly pine in response to cultural management. LSU Forestry Notes No. 88, Louisiana State University. LA. 3pp.

Clark III, A., B. E. Borders and R. F. Daniels. 2004. Impact of vegetation control and annual fertilization on properties of loblolly pine wood at age 12. Forest Prod. J. 54: 90 – 96.

Downes, G. M., J. G. Nyakuengama, R. Evans, R. Northway, P. Blakemore, R. L. Dickson and M. Lausberg. 2002. Relationship between wood density, microfibril angle and stiffness in thinned and fertilized *Pinus radiate*. IAWA Jour. 23: 253-265.

Erickson, H. D. and T. Arima. 1974. Douglas-Fir wood quality studies part II: Effects of age and stimulated growth on fibril angle and chemical constituents. Wood Science and Technology. 8: 255-265.

Forest Nutrition Cooperative Synthesis. 2006. Web resource obtained from: http://www.forestnutrition.org/synthesis.htm prepared by Allen, H. L., T. R. Fox and T. J. Albaugh.

Hoag, M. L. and R. L. Kramer. 1991. Polychromatic x-ray attenuation characteristics and wood densitometry applications. Wood Fiber Sci. 23: 23 – 31.

Larson, P. R., D. E. Kretschmann., A. Clark III and J. G. Isebrands. 2001. Formation and properties of juvenile wood in southern pines. General Technical Report (FPL –GTR-129). United States Department of Agriculture (Forest Service). 42pp.

Mallonee, E. H. 1975. Effect of thinning and seasonal time of Nitrogen fertilization on the growth of pole sized loblolly pine. Thesis. Dept. of For. N.C. State University. Raleigh, N. C.

Megraw, R. A. 1985. Wood quality factors in loblolly pine. TAPPI Press. 88pp.

Megraw, R. A., D. Bremer, G. Leaf, and J. Roers. 1999. Clearwood stiffness variation in loblolly pine and its relationship to specific gravity and microfibril angle. Proceedings of the third workshop – Connection between silviculture and wood quality through modeling approaches; working party S5: 01-04; La londe-les-maures. Sept 5-12, pp 341-349.

Mora, C. R. 2003. Effects of early intensive silviculture on wood properties of loblolly pine. MS Thesis. Dept. of For. NC State University. Raleigh. NC.

Morling, T. 2002. Evaluation of annual ring width and ring density development following fertilization and thinning of scots pine. Ann. For. Sci. 59: 29 – 40.

Nyakuengama, J. G. 1991. The physical and chemical properties of superior radiate pine (*Pinus radiata* D. Don) wood for thermo-mechanical pulping compared with standarad radiate pine. B. Sc. Hons. Thesis. Dept. of For., Australian National University. Canberra, Australia.

Nyakuengama, J. G., G. M. Downes and J. Ng. 2002. Growth and wood density responses to later-age fertilizer application in *Pinus radiata*. IAWA J. 23: 431 – 448.

Nyakuengama, J. G., G. M. Downes and J. Ng. 2003. Changes caused by mid-rotation fertilizer application to the fiber anatomy of *Pinus radiata*. IAWA J. 24: 397 – 409.

Nyakuengama, J. G., G. M. Downes, E. K. S. Nambiar, P. Blakemore and R. N. Northway. 2004. Effect of later age stand management on quality of radiate pine wood. Forest and Wood Products Research and Development Corporation. Project Report. 33pp.

Posey, C. E. 1964. The effect of fertilization upon wood properties of loblolly pine. Technical Report No. 22. School of Forestry. N. C. State University. Raleigh, N.C. 63pp.

Ross, D., E. Buckner., H. Core and F. Woods. 1979. Nitrogen fertilization decreases yellow poplar wood density. South. J. Appl. For. 3: 119 – 122.

SAS Institute, Inc. 2004. SAS/STAT User's Guide, Version 9.1, Cary, NC: SAS Institute, Inc. 4975.p.

Williams, R. F. and J. R. Hamilton. 1961. The effect of fertilization on four wood properties of slash pine. J. of For. 59: 662 – 665.

Zobel, B. J., G. F. Groggans, T. E. Maki, and F. Henson. 1961. Some effects of fertilizers on wood properties of loblolly pine. TAPPI. 44(3):187-191.

TABLES AND FIGURES FOR CHAPTER 3

Table 3.1: Test statistics for the analysis of whole core weighted average wood properties by height level and fertilization treatment.

Property	**Source**	**Numerator *d.f.***	**Denominator *d.f.***	**F-Value**	**P-Value**	σ^2_T	σ^2
	H	5	139	125.80	<0.0001		
WSG	F	3	12	1.71	0.2179	$2.7X10^{-4}$	$2.9X10^{-4}$
	H*F	15	139	1.54	0.0998		
	H	5	15.9	9.33	0.0003		
WLG	F	3	27.6	2.16	0.1160	$2.8X10^{-4}$	$3.2X10^{-4}$
	H*F	15	124	0.99	0.4713		
	H	5	139	193.99	<0.0001		
WLP	F	3	12	0.88	0.4786	5.8	7.8
	H*F	15	139	1.09	0.3725		
	H	5	14.7	7.83	0.0009		
WEG	F	3	11.6	1.37	0.2994	$1.4X10^{-4}$	$1.5X10^{-4}$
	H*F	15	124	1.30	0.2144		

WSG = Weighted ring specific gravity; **WLG** = Weighted latewood specific gravity; **WLP** = Weighted latewood percent; **WEG** = Weighted earlywood specific gravity; **H** = Height; **F** = Fertilizer treatment; **H*F** = Interaction between height and fertilizer treatment

Table 3.2: Least square means of basal area weighted whole-core average of wood properties by treatments.

	Treatments			
Property	**Control**	**100lb/acre**	**200lb/acre**	**300lb/acre**
Ring Specific gravity	0.4569	0.4714	0.4708	0.4490
Latewood Specific gravity	0.7025	0.7184a	0.7061	0.6955a
Latewood Percent	38.42	40.69	40.04	37.96
Earlywood Specific gravity	0.3034	0.3020	0.3130	0.2972

***values with same letter in the row are significantly different at p<0.1

Table 3.3: Least square means of basal area weighted whole-core average of wood properties by height level.

	Heights					
Property	**4.5 feet**	**10 feet**	**15 feet**	**25 feet**	**35 feet**	**45 feet**
Ring Specific gravity	0.5163ab	0.4834ab	0.4659abc	0.4465abcd	0.4374abc	0.4226abcd
Latewood Specific gravity	0.7111a	0.7218b	0.7118c	0.7074d	0.6999be	0.6818abcde
Latewood Percent	50.39a	42.92ab	40.74abc	36.22abcd	34.05abcde	31.55abcde
Earlywood Specific gravity	0.3188a	0.3044a	0.2969a	0.2984a	0.3014a	0.3040a

***values with same letter in the row are significantly different at p<0.1

Table 3.4: Test statistics on the analysis of three year post fertilization weighted average of key wood properties.

Property	Source	Numerator *d.f.*	Denominator *d.f.*	F-Value	P-Value	σ^2_T	σ^2
MOE	H	5	134	73.90	<0.0001	0.8	3.0
	F	3	28.2	3.37	0.0324		
	H*F	15	134	0.72	0.7565		
WSG	H	5	129	93.24	<0.0001		$9.7X10^{-4}$
	F	3	9.1	5.40	0.0209		
	H*F	15	132	0.94	0.5271		
WLG	H	5	13.5	58.85	<0.0001	$1.9X10^{-4}$	$9.8X10^{-4}$
	F	3	28.2	11.07	<0.0001		
	H*F	15	119	0.65	0.8292		
WLP	H	5	13.1	95.46	<0.0001	8.3	27.9
	F	3	9.1	4.37	0.0365		
	H*F	15	116	1.87	0.0335		
WEG	H	5	15.1	12.17	<0.0001	$1.4X10^{-5}$	$3.8X10^{-4}$
	F	3	11.3	1.82	0.2008		
	H*F	15	96.2	1.33	0.2011		
MFA	H	5	124	54.50	<0.0001		10.48
	F	3	12.1	1.68	0.2231		
	H*F	15	130	0.95	0.5154		
Wall Thickness	H	5	134	193.63	<0.0001	$2.3X10^{-2}$	$4.7X10^{-2}$
	F	3	12.1	1.94	0.1771		
	H*F	15	134	0.63	0.8490		
Radial Diameter	H	5	121	34.43	<0.0001		3.6
	F	3	11	4.61	0.0253		
	H*F	15	129	1.32	0.1974		
Tangential Diameter	H	5	97.3	29.52	<0.0001		1.2
	F	3	11.3	2.09	0.1587		
	H*F	15	112	1.02	0.4446		
Coarseness	H	5	134	48.34	<0.0001	533.4	2939.9
	F	3	28.5	0.65	0.5925		
	H*F	15	134	0.85	0.6220		
Perimeter	H	5	118	30.18	<0.0001		34.5
	F	3	10.7	4.31	0.0315		
	H*F	15	126	1.23	0.2615		
Specific Surface	H	5	135	183.5	<0.0001		469.4
	F	3	12.3	1.95	0.1739		
	H*F	15	135	0.68	0.8020		

MOE = Modulus of elasticity; **WSG** = Weighted ring specific gravity; **WLG** = Weighted latewood specific gravity; **WLP** = Weighted latewood percent; **WEG** = Weighted earlywood specific gravity; **MFA** = Microfibril angle.

Table 3.5: Least square means of basal area weighted three year average of wood properties by fertilization treatment.

	Treatments			
Property	**Control**	**100lb/acre**	**200lb/acre**	**300lb/acre**
Modulus of Elasticity (GPa)	11.40	11.99a	10.74	10.27a
Ring Specific gravity	0.4422a	0.4525b	0.4464c	0.4116abc
Latewood Specific gravity	0.6738a	0.6912b	0.6580b	0.6379ab
Latewood Percent	34.55	36.44a	37.72b	29.18ab
Earlywood Specific gravity	0.3093	0.3062	0.3199	0.3061
Microfibril Angle (in degrees)	18.66	18.34	20.60	20.73
Wall Thickness (μm)	3.43	3.50	3.48	3.27
Radial Diameter (μm)	36.93a	37.03b	36.86c	38.46abc
Tangential Diameter (μm)	33.18	33.61	33.16	33.87
Coarseness (μg/m)	557.31	569.69	565.96	549.05
Perimeter (μm)	140.41a	141.53	140.22b	144.80ab
Specific Surface (m^2/kg)	283.20	275.59	280.65	295.80

***values with same letter in the row are significantly different at p<0.1

Table 3.6: Least square means of basal area weighted three-year average of wood properties by height level.

	Heights					
Property	**4.5 feet**	**10 feet**	**15 feet**	**25 feet**	**35 feet**	**45 feet**
Modulus of Elasticity (GPa)	13.65a	13.32b	13.18c	10.92abcd	8.91abcde	6.61abcde
Ring Specific gravity	0.5287a	0.4813abc	0.4551abc	0.4109abcd	0.3801abcd	0.3730abcd
Latewood Specific gravity	0.7018a	0.7018b	0.6988c	0.6743abd	0.6487abce	0.5658abcde
Latewood Percent	54.93a	44.88ab	39.91ac	29.53abcd	20.53abcd	15.56abcd
Earlywood Specific gravity	0.3172a	0.3013b	0.2933ac	0.2989d	0.3099e	0.3416abcde
Microfibril Angle (in degrees)	21.40a	16.68ab	14.71abc	16.46ad	20.56bcde	27.68abcde
Wall Thickness (μm)	4.16a	3.84ab	3.65abc	3.25abcd	2.91abcde	2.71abcde
Radial Diameter (μm)	34.14a	36.41ab	36.78ac	37.98abcd	37.95abe	40.67abcde
Tangential Diameter (μm)	32.40a	33.10ab	32.99c	33.25ad	33.20ae	35.80abcde
Coarseness (μg/m)	626.61a	630.74b	598.91c	549.19abcd	486.43abcd	471.14abcd
Perimeter (μm)	133.26a	139.46ab	139.80ac	142.71ad	142.60ae	152.60abcde
Specific Surface (m^2/kg)	223.26a	243.59ab	257.25abc	283.69abcd	315.78abcde	379.30abcde

***values with same letter in the row are significantly different at $p<0.1$

Table 3.7: Test statistics from repeated measure analysis of the five year post fertilization value

Property	Source	Numerator *d.f.*	Denominator *d.f.*	F-Value	P-Value	σ^2_T	σ^2
RSG	F	3	11.8	2.47	0.1131		$5.3X10^{-4}$
	H	5	66.8	132.30	<0.0001		
	A	4	65.3	12.35	<0.0001		
	H*F	15	66.3	2.20	0.0148		
	A*F	12	65.1	2.27	0.0179		
	H*A*F	60	288	2.41	<0.0001		
LWSG	F	3	33.2	4.05	0.0147		$2.3X10^{-4}$
	H	5	89.5	38.54	<0.0001		
	A	4	242	19.61	<0.0001		
	H*F	15	89.4	0.65	0.8246		
	A*F	12	241	1.89	0.0356		
	H*A*F	60	313	0.94	0.6019		
LWP	F	3	12.2	1.19	0.3544		25.7
	H	5	111	269.93	<0.0001		
	A	4	91.8	15.53	<0.0001		
	H*F	15	110	5.42	<0.0001		
	A*F	12	87.9	4.41	<0.0001		
	H*A*F	60	315	3.96	<0.0001		
EWSG	F	3	43	6.89	0.0007		$1.3X10^{-4}$
	H	5	66.4	9.65	<0.0001		
	A	4	115	10.27	<0.0001		
	H*F	15	66.2	6.21	<0.0001		
	A*F	12	112	11.28	<0.0001		
	H*A*F	60	302	3.82	<0.0001		

RSG = Ring specific gravity; **LWSG** = Latewood specific gravity; **LWP** = Latewood percent; **EWSG** = Earlywood specific gravity; **F** = Fertilizer treatment; **H** = Height; **A** = Year; **H*F** = Interaction between height and fertilizer treatment; **A*H** = Interaction between height and year; and **H*A*F** = Interaction among terms fertilizer treatment, year and height.

Table 3.8: Least square means of ring specific gravity for each treatment by height level for the five years following fertilization.

Height	**Treatment**	**Year**				
		1984	1985	1986	1987	1988
4.5	000N	0.5360	0.5369	0.5193	0.4891	0.4565
	100N	0.5428	0.5534	0.5420	0.5359	0.5089
	200N	0.5246	0.5454	0.5528	0.5485	0.5276
	300N	0.4881	0.5045	0.5074	0.5330	0.5124
10	000N	0.4983	0.4928	0.4876	0.4748	0.4457
	100N	0.4943	0.5060	0.5092	0.4985	0.4833
	200N	0.4763	0.4794	0.4950	0.4949	0.4598
	300N	0.4458	0.4441	0.4611	0.4645	0.4509
15	000N	0.4559	0.4671	0.4562	0.4577	0.4320
	100N	0.4848	0.4790	0.4769	0.4644	0.4358
	200N	0.4472	0.4516	0.4677	0.4818	0.4582
	300N	0.3986	0.4414	0.4413	0.4718	0.4342
25	000N	0.4007	0.4270	0.4328	0.4162	0.4002
	100N	0.4062	0.4428	0.4428	0.4581	0.4109
	200N	0.3960	0.4040	0.4329	0.4348	0.4096
	300N	0.3620	0.3944	0.3957	0.4345	0.3998
35	000N	0.3586	0.4074	0.3876	0.4072	0.3745
	100N	0.3720	0.3936	0.3977	0.3887	0.3875
	200N	0.3644	0.4003	0.3942	0.3980	0.3864
	300N	0.3260	0.3629	0.3717	0.3879	0.3785
45	000N	0.3960	0.3955	0.3777	0.3616	0.3402
	100N	0.3416	0.3571	0.3599	0.3528	0.3485
	200N	0.4790	0.4329	0.3927	0.3737	0.3519
	300N	0.5416	0.3335	0.3489	0.3443	0.3356

Table 3.9: Least square means of latewood specific gravity for each treatment for the five years following fertilization.

Treatments	**Year**				
	1984	1985	1986	1987	1988
000N	0.6671	0.6724	0.6786	0.6756	0.6918
100N	0.6422	0.6870	0.6941	0.7137	0.7111
200N	0.6303	0.6435	0.6869	0.6875	0.7035
300N	0.6079	0.6348	0.6555	0.6768	0.6742

Table 3.10: Least square means of percent latewood for each treatment by height level for the five years following fertilization.

Height	Treatment	Year				
		1984	1985	1986	1987	1988
4.5	000N	56.21	55.93	54.92	49.91	41.28
	100N	60.31	55.45	57.05	52.96	50.30
	200N	55.34	56.20	55.22	54.81	51.72
	300N	51.50	52.39	50.28	55.64	51.08
10	000N	45.77	46.79	46.84	42.71	34.89
	100N	48.15	46.41	47.32	42.61	40.90
	200N	46.61	43.28	44.73	45.76	35.06
	300N	44.34	39.85	41.72	42.51	38.81
15	000N	37.02	40.59	40.47	39.14	34.85
	100N	46.11	41.28	41.77	39.59	32.62
	200N	41.22	43.20	41.48	42.40	36.63
	300N	30.64	38.95	37.00	43.25	32.75
25	000N	24.42	32.99	33.84	30.55	26.31
	100N	29.32	35.54	37.74	39.59	28.45
	200N	28.96	27.05	34.41	36.09	26.71
	300N	20.07	24.61	27.90	36.56	27.16
35	000N	18.00	25.85	22.87	28.59	20.19
	100N	17.61	20.86	26.28	24.50	23.26
	200N	15.37	23.36	25.01	27.16	21.16
	300N	10.96	14.92	19.60	24.60	20.44
45	000N	7.24	12.99	13.76	10.60	11.75
	100N	6.06	10.41	17.06	15.63	14.94
	200N	59.94	32.81	20.21	14.34	11.20
	300N	98.39	10.17	7.35	9.71	10.81

Table 3.11: Least square means of earlywood specific gravity for each treatment by height level for the five years following fertilization.

Height	Treatment	Year				
		1984	1985	1986	1987	1988
4.5	000N	0.3193	0.3113	0.3068	0.2973	0.2909
	100N	0.3158	0.3115	0.3097	0.3084	0.2998
	200N	0.3460	0.3155	0.3266	0.3279	0.3261
	300N	0.3232	0.3106	0.3151	0.3183	0.3112
10	000N	0.3135	0.3045	0.2976	0.2943	0.2988
	100N	0.3038	0.2987	0.3010	0.3063	0.3103
	200N	0.3098	0.2971	0.2979	0.2973	0.3062
	300N	0.2994	0.2972	0.2969	0.2923	0.2925
15	000N	0.3004	0.2945	0.2879	0.2870	0.2880
	100N	0.3023	0.2996	0.2969	0.2863	0.2975
	200N	0.2992	0.2848	0.2913	0.3007	0.2979
	300N	0.2906	0.2930	0.2864	0.2855	0.2972
25	000N	0.3028	0.3045	0.2944	0.2896	0.2912
	100N	0.2883	0.2988	0.2892	0.2862	0.2897
	200N	0.3010	0.3032	0.2956	0.2907	0.2954
	300N	0.3012	0.3154	0.2882	0.2872	0.2898
35	000N	0.2970	0.3142	0.3018	0.3013	0.2935
	100N	0.3228	0.3171	0.2980	0.2939	0.2906
	200N	0.3166	0.3208	0.3039	0.2970	0.3010
	300N	0.2974	0.3197	0.3121	0.3091	0.3085
45	000N	0.3932	0.3827	0.3430	0.3245	0.2978
	100N	0.3316	0.3302	0.3137	0.2980	0.2945
	200N	0.4242	0.3909	0.3556	0.3338	0.3137
	300N	-0.0098	0.3141	0.3349	0.3176	0.2999

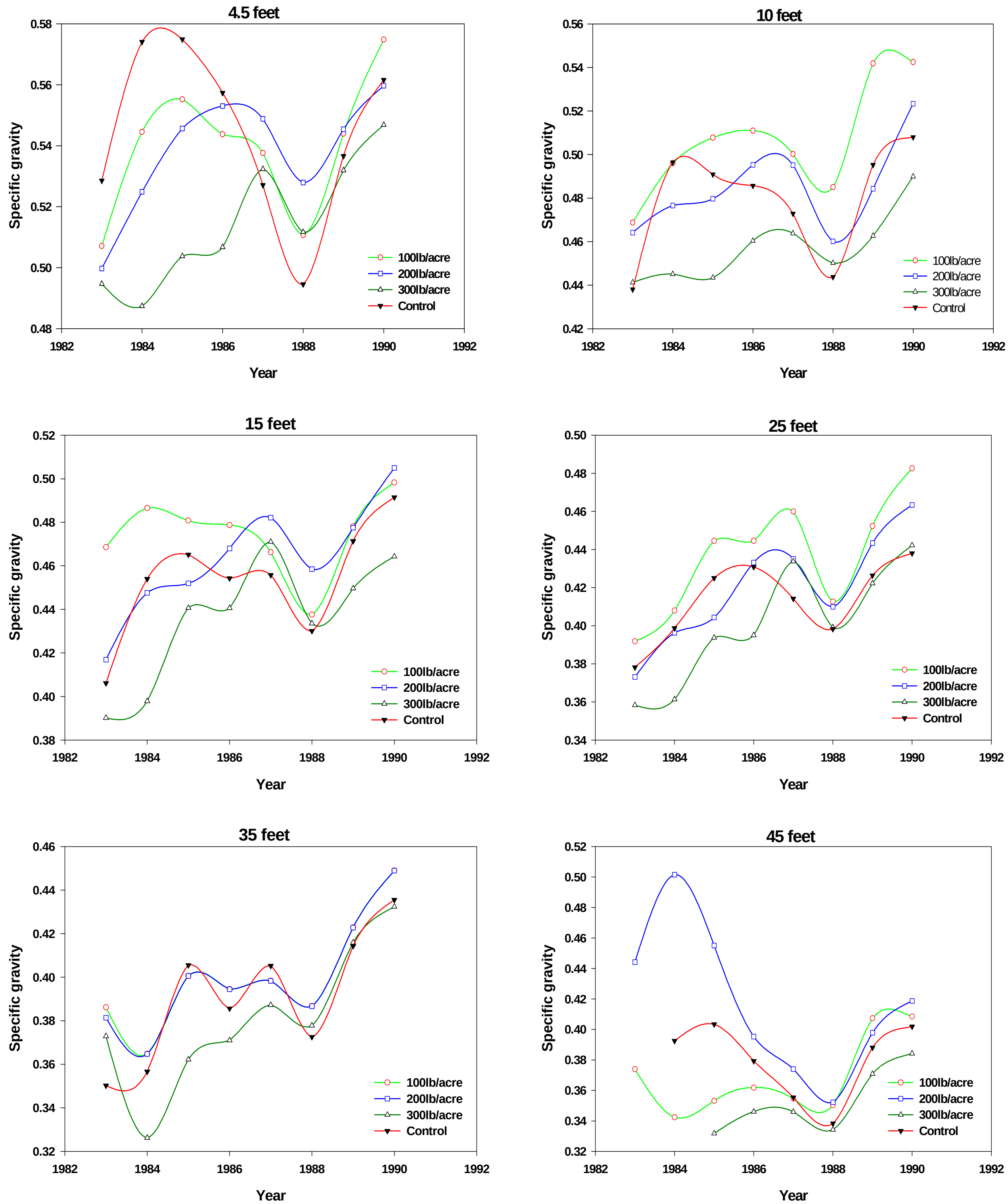

Figure 3.1: Average ring specific gravity by year (1983 to 1990) for four (100N, 200N, 300N and Control) levels of fertilizer application.

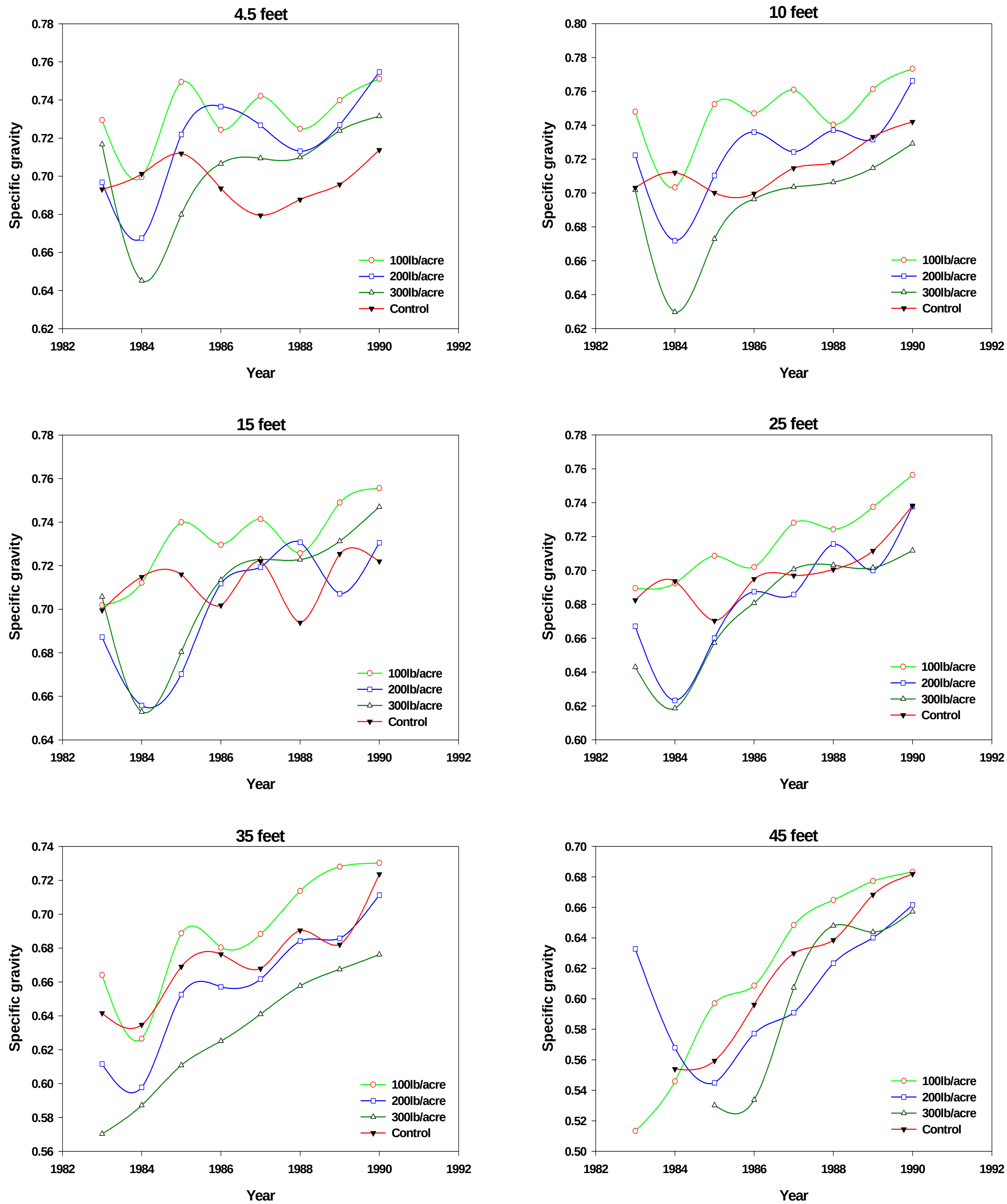

Figure 3.2: Average latewood specific gravity by year (1983 to 1990) for four (100N, 200N, 300N and Control) levels of fertilizer application.

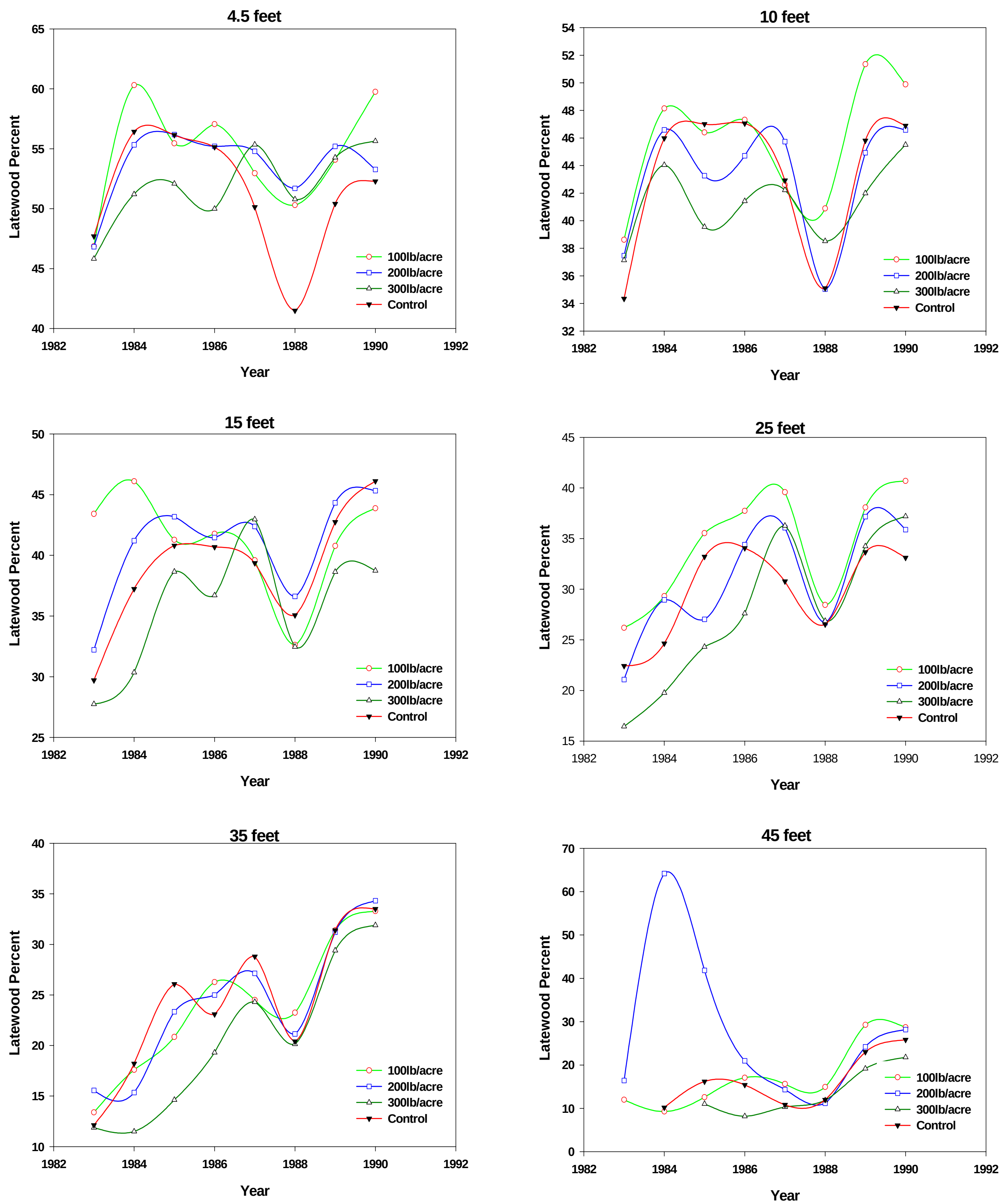

Figure 3.3: Average latewood percent by year (1983 to 1990) for four (100N, 200N, 300N and Control) levels of fertilizer application.

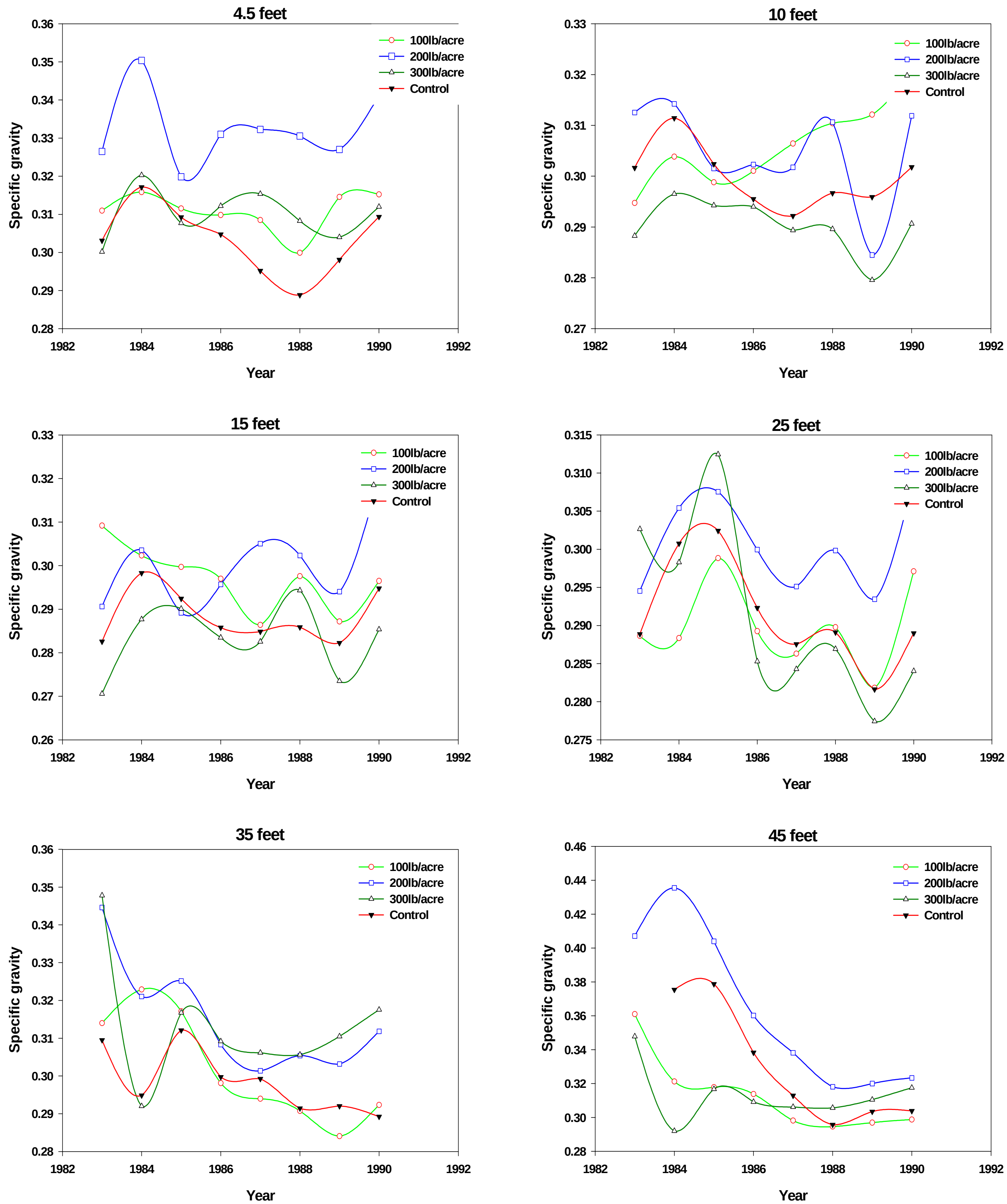

Figure 3.4: Average earlywood specific gravity by year (1983 to 1990) for the four (100N, 200N, 300N and Control) levels of fertilizer application.

CHAPTER 4

MODELING THE EFFECTS OF FERTILIZATION ON STIFFNESS OF LOBLOLLY PINE (*PINUS TAEDA* L.)

ABSTRACT

Modulus of elasticity (MOE) or stiffness was measured from radial strips collected at six height levels from a thinned and fertilized mid-rotation loblolly pine (*Pinus taeda* L.) plantation located in the Coastal Plain of North Carolina. The study was a randomized complete block design receiving four levels of nitrogen fertilizer (Control- no fertilizer, 100lb/acre, 200lb/acre and 300lb/acre along with 25lb/acre of phosphorous with each treatment), each replicated in four blocks. A nonlinear logistic model was fitted to explain the variation in stiffness in a three dimensional way, from stump to tip and pith to bark of a tree which did not receive any mid-rotation fertilizer application. Attempts were made to explain the differences in stiffness of wood formed following fertilizer application. However, the lack of consistent response in stiffness from stump to tip and pith to bark owing to fertilization made the explanation of stiffness response in a functional form difficult.

Keywords: loblolly pine, stiffness, nonlinear modeling, fertilization

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is one of the major commercial tree crops in the southern United States of America (USA). This region alone supplies around 58% of total wood used in the USA and 16% of the wood supplied to the world market (Wear and Greis 2002). Considering the importance of this species, various research efforts and field trials were established to improve the gain in yield from a unit area of production. Application of intensive silvicultural management practices along with the use of genetically improved seedlings proved to be successful in shifting the growth curve of this species upwards (Li *et al*. 1999, Amateis *et al.* 2000, Jokela *et al*. 2000, Borders and Bailey, 2001). However, the supply of timber to the market produced from intensively managed plantations has increased in the last couple of decades; there is a vital need to examine the quality of wood produced following these silvicultural practices.

Modulus of elasticity (MOE) / Stiffness is an important wood quality parameter. Simply MOE is explained as the ability of wood to withstand a load. The MOE within a tree depends upon the radial position and height within a tree. MOE increases from pith to bark within a tree and decreases from stump to tip (Megraw *et al*. 1999). Ring specific gravity and microfibril angle are considered to be major contributors to the stiffness of wood. A direct positive relationship exists between MOE and specific gravity, while an inverse relationship exists between MOE and microfibril angle (Megraw *et al*. 1999).

Mid-rotation application of nitrogen fertilizer is gaining considerable interest in loblolly pine management because of its ability to improve yield in a biologically and financially attractive way (FNC Synthesis 2006). However concerns exist about the quality of wood produced by these practices. The ability to predict MOE anywhere within the tree would significantly improve the utilization performance of wood produced following silvicultural practices especially mid-rotation fertilization. More over, such models would help industry to optimize the purchase and utilization of wood for appropriate products and let growers to project the quality of future products from various silvicultural practices.

The objective of this study was to develop a basic model to predict the MOE of loblolly pine at any point within the tree, from pith to bark and from stump to tip. The specific objective was to identify the trend of MOE change at different height levels within the tree following fertilization and to try to incorporate this response function in the basic model which will aid foresters in predicting the MOE of wood formed following mid-rotation fertilization of loblolly pine plantations.

MATERIALS AND METHODS

DATA COLLECTION

In addition to the 1 inch X 1 inch X 1 inch blocks, an additional 36 strips (selected to represent the 6 height level within each treatment) of length 40 mm were randomly separated from the mature and juvenile wood regions of the pith to bark radial strips. This set was also sent for the estimation of stiffness by SilviScan.

Near infrared (NIR) reflectance spectra were collected from the radial face of all SilviScan strips at an interval of 10 mm using a NIRSystems Inc. Model 5000 scanning spectrophotometer. All spectra were collected in a light proof environment to avoid any intervention of stray light on NIR measurements. A 10 mm X 5 mm mask was used to ensure a constant area was tested. The SilviScan data and spectra collected from SilviScan strips using the NIR Systems 5000 scanning spectrophotometer were used to develop a Partial Least Square (PLS) regression calibration for the prediction of stiffness. The calibration was developed using

Unscarmbler Software (Version 9.2). This calibration was used for the prediction of stiffness from pith to bark at 10 mm intervals from NIR spectra collected from the radial strips cut at the USDA-Forest Service wood property lab.

Non-linear models for predicted stiffness were fitted using data from every 10mm interval, pith- to- bark, at six height levels using PROC NLIN and PROC MODEL procedures available in the SAS version 9.1 (SAS 2004).

MODEL DEVELOPMENT

The first step was to develop a basic model which can explain the variation in MOE from pith to bark at different height levels for a tree growing under normal conditions where no fertilizer treatment was received. MOE data at each point were plotted from pith to bark at six height levels (Figure 4.1) irrespective of treatment applied. MOE follows a non-linear pattern of increase with distance from the pith at all heights (Figure 4.1 and 4.2). A logistic function was selected from several candidate models to explain the variation in MOE from pith to bark. The functional form of the model is:

$$f(x) = \frac{\phi_1}{1 + (\phi_2 * \exp(\phi_3 * x))}$$

For prediction of MOE, at any given height level the model becomes:

$$MOE_{ij} = \frac{\phi_1}{1 + (\phi_2 * \exp(\phi_3 * dist_i)} + \varepsilon_{ij}$$

where,

MOE_{ij} = modulus of elasticity at i^{th} distance from pith and j^{th} height,

$dist$ = distance from pith to bark,

ϕ_1, ϕ_2, ϕ_3 = parameters to be estimated from the data,

ε_{ij} = random error associated with distance i, at height j.

The three dimensional explanation of MOE was possible only by incorporating the height term in the model. According to Daniels *et al*. (2002), a simplest solution to this problem is to predict the parameters in the above equation as quadratic functions of height. Thus the parameters in the above equation can be written as:

$$\hat{\phi}_1 = b_{01} + b_{11}H_j + b_{21}H_j^2$$

$$\hat{\phi}_2 = b_{02} + b_{12}H_j + b_{22}H_j^2$$

$$\hat{\phi}_3 = b_{03} + b_{13}H_j + b_{23}H_j^2$$

where,

H_j = tree height above ground at disk j,

b_{01},…..b_{23} = parameters to be estimated.

FITTING THE RESPONSE MODEL

After fitting the basic model for predicting MOE at any point within the tree, attempts were made to fit the pattern of response observed for MOE at any position following fertilizer application. Average MOE by treatment and difference in average MOE of the treatments (100N, 200N and 300N) from 000N were calculated at each position (10mm interval) from the point of fertilization to bark and plotted at six height levels (Figure 4.3 and 4.4).

RESULTS

Table 4.1 contains the parameter estimates and fit index of the nonlinear MOE model. Two of the parameters in the proposed model (b_{11}, b_{22}) were found to be not significant and dropped from the final model. The final three dimensional MOE prediction model is given as:

$$M\hat{O}Eij = \frac{16.2065 - 0.0013h_j^{\,2}}{1 + \left[(6.9039 - 0.1107h_j)\exp\left(\left(-0.0382 - 0.0018h_j + 0.00003h_j^{\,2}\right) \times dist_i\right)\right]}$$

All other parameters in the model were significant at the 0.05 level. Plots of residuals against independent variables height and distance from pith (Figure 4.5) did not show any trend that would indicates bias. The plot of residuals against fitted values did not show any specific pattern either (Figure 4.5). The plot of actual MOE values versus fitted MOE values shows a reasonable relationship (Figure 4.5). It was also observed that the mean of fitted values and actual values did not vary greatly at six height levels (Figure 4.6).

DISCUSSION

A nonlinear logistic model was developed to explain the variation in MOE at any point within the tree based on the data collected from 32 trees at six height levels. The fit index (R^2) of this model was 0.7293 with a residual standard error of 2.1589 GPa. From the examination of the fit index, residual plots and plots of fitted values with actual values, the proposed model was found to perform reasonably well in explaining changes in MOE from pith to bark and stump to tip of a tree. From a utilization point of view, the basic model will aid the forester to predict MOE at any point within a tree. Moreover the model needs minimal inputs, radial distance from pith and height of the sample in the tree, which are easy to measure compared to MOE prediction models which use microfibril angle and ring specific gravity as predictive variables.

Various studies examined the changes in physical, mechanical and anatomical properties of wood produced in different species following mid-rotation fertilization (Williams and Hamilton 1961 - *Pinus elliotti* Engelm., Posey 1964 – *Pinus taeda* L., *Pinus radiata* D.Don - Nyakuengama *et al*. 2002, Nyakuengama *et al.* 2003, Nyakuengama *et al*. 2004), but none attempted to model the response in a predictive format. This is the first endeavor to fit a common function for response owing to treatments across height levels. However, the attempt to model the treatment response on MOE failed due to the absence of a consistent response following mid-rotation fertilization from stump to tip and from pith to bark (Fig 4.3 & 4.4). Even though the attempt to model the treatment response for MOE failed, it was clear from the plots of response (Figure 4.4) that at height levels 4.5 and 10 feet, the application of nitrogen (particularly 100N) resulted in the production of wood which was stiffer than untreated trees, except for a small decline in stiffness immediately after fertilization for higher rates of nitrogen (200N and 300N) applications. At height levels 15 and 25 feet, 100N produced stiffer wood, while stiffness for the 200N and 300N treatments decreased after treatment before becoming normal. At heights 35 and 45 feet, all levels of nitrogen application resulted in the production of less stiff wood. This might be explained by the differences in the type of wood being produced at each height. At the lower heights (4.5 and 10 feet) the trees have started to produce mature wood with higher latewood content. Application of nitrogen at mid-rotation produced little change in wood quality at these heights except for a temporary decrease for higher treatment rates. As height increased (15 and

25 feet) the trees are in the transition stage between maturity and juvenility. The higher rate of nitrogen application resulted in a decline in wood quality or an extension of the transition period at these heights. At heights 35 and 45 feet, which are close to crown, application of nitrogen resulted in production of more juvenile wood of lower quality.

REFERENCES

Amateis, R. L., J. Liu, M. J. Ducey and H. L. Allen. 2000. Modeling response to mid-rotation Nitrogen and Phosphorous fertilization in loblolly pine plantations. South. J. Appl. For. 24: 207 – 212.

Borders, B. E. and R. L. Bailey. 2001. Loblolly pine-pushing the limits of growth. South. J. Appl. For. 25(2):69-74.

Daniels, R. F., H. E. Rechun, A. Clark III, and R. A. Souter, 2002. Modeling wood properties of planted loblolly pine from pith to bark and stump to tip. Proceedings of fourth Workshop IUFRO S5.01.04. Canada. 238-245.

Forest Nutrition Cooperative Synthesis. 2006. Web resource obtained from: http://www.forestnutrition.org/synthesis.htm prepared by Allen, H. L., T. R. Fox and T. J. Albaugh.

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.

Li, B., S. McKeand and R. Weir. 1999. Tree improvement and sustainable forestry-impact of two cycles of loblolly pine breeding in the USA. For. Gen. 6: 229-234.

Megraw, R. A., D. Bremer, G. Leaf, and J. Roers. 1999. Clearwood stiffness variation in loblolly pine and its relationship to specific gravity and microfibril angle. Proceedings of the third workshop – Connection between silviculture and wood quality through modeling approaches; working party S5: 01-04; La londe-les-maures. Sept 5-12, pp 341-349.

NCSFNC Report No. 39. 1997. North Carolina Forest Nutrition Cooperative. Department of Forestry. North Carolina State University. Raleigh, NC.

Nyakuengama, J.G., G.M. Downes, and J. Ng. 2002. Growth and wood density responses to later-age fertilizer application in *Pinus radiata*. IAWA J. 23(4): 431-448.

Nyakuengama, J. G., G. M. Downes, and J. Ng. 2003. Changes caused by mid-rotation fertilizer application to the fiber anatomy of *Pinus radiata*. IAWA J. 24(4): 397-409.

Nyakuengama, J. G., G. M. Downes, E. K. S. Nambiar, P. Blakemore and R. N. Northway. 2004. Effect of later age stand management on quality of radiate pine wood. Forest and Wood Products Research and Development Corporation. Project Report. 33pp.

Posey, C. E. 1964. The effect of fertilization upon wood properties of loblolly pine. For. Tree Improv. Program. Sch. For. North Carolina State Univ. Tech. Rep. No. 22. 61pp.

SAS Institute, Inc. 2004. SAS/STAT User's Guide, Version 9.1, Cary, NC: SAS Institute, Inc. 4975.p.

Wear, D. N., and J. G. Greis. 2002. Southern Forest Resource Assessment: Summary of Findings. J. For. 100(7): 6-14.

Williams, R. F. and J. R. Hamilton. 1961. The effect of fertilization on four wood properties of Slash pine. J. For. 59: 662-665.

TABLES AND FIGURES FOR CHAPTER 4

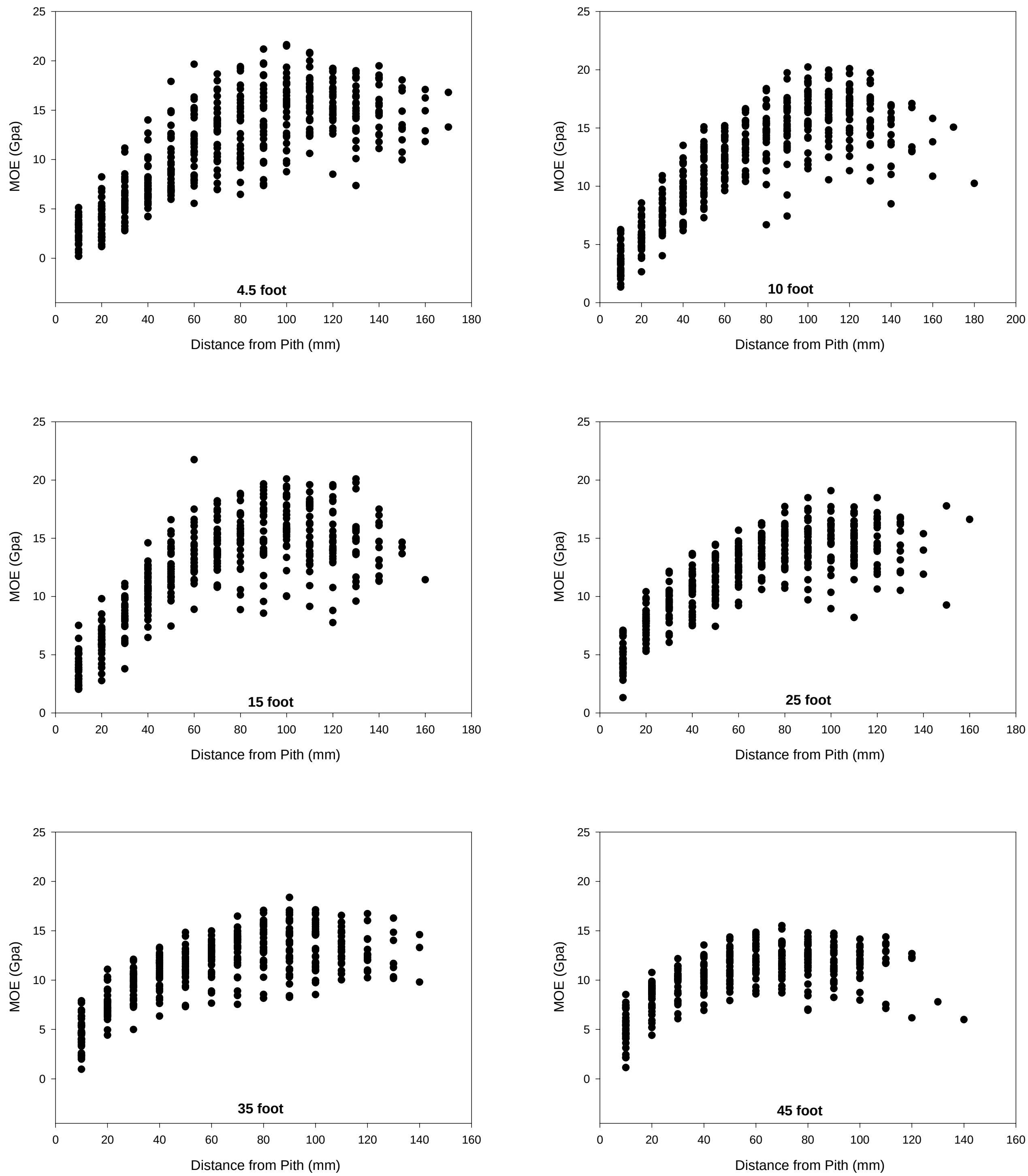

Figure 4.1: Plots of modulus of elasticity (MOE) versus radial distance at different height levels.

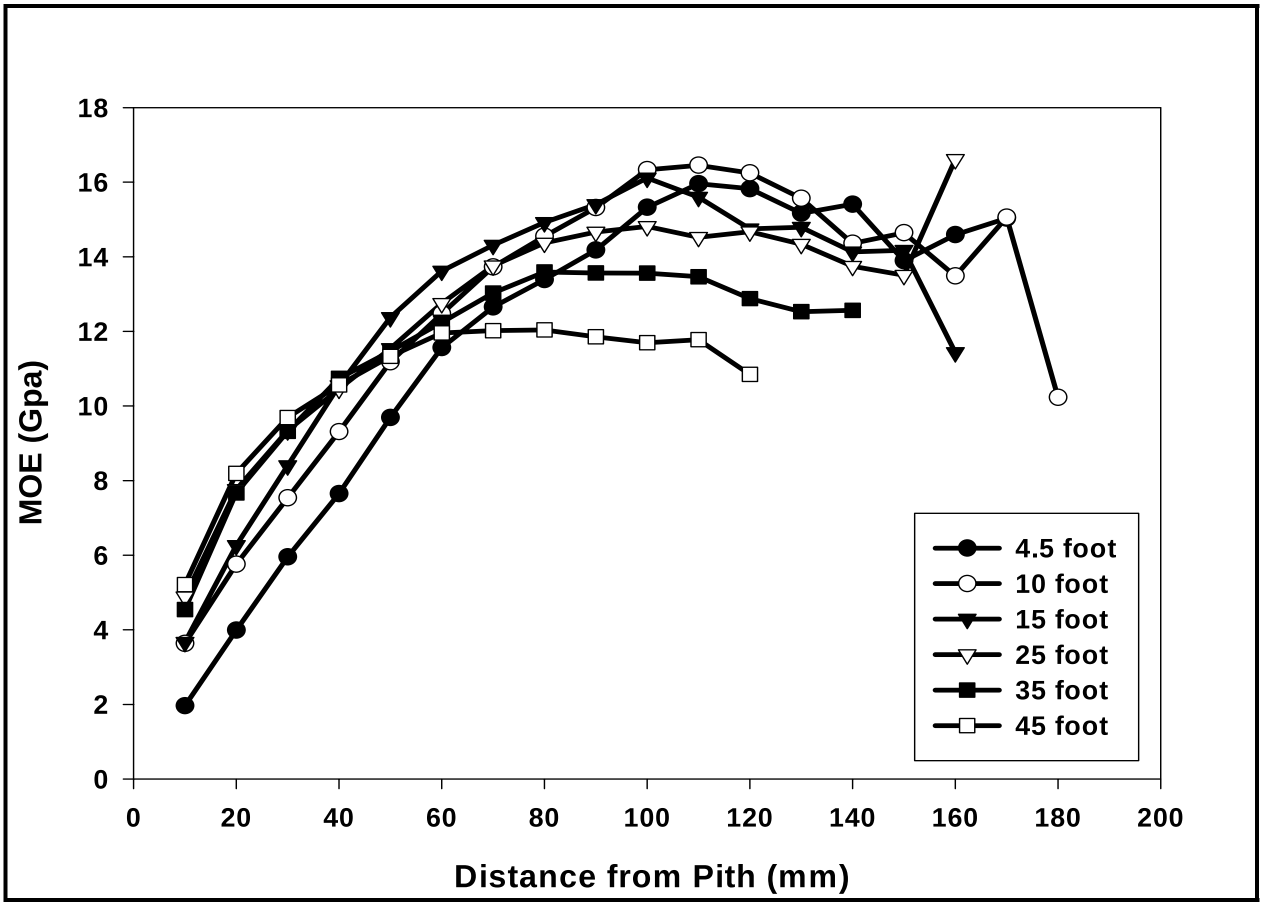

Figure 4.2: Plot of average modulus of elasticity (MOE) versus radial distance by disk height.

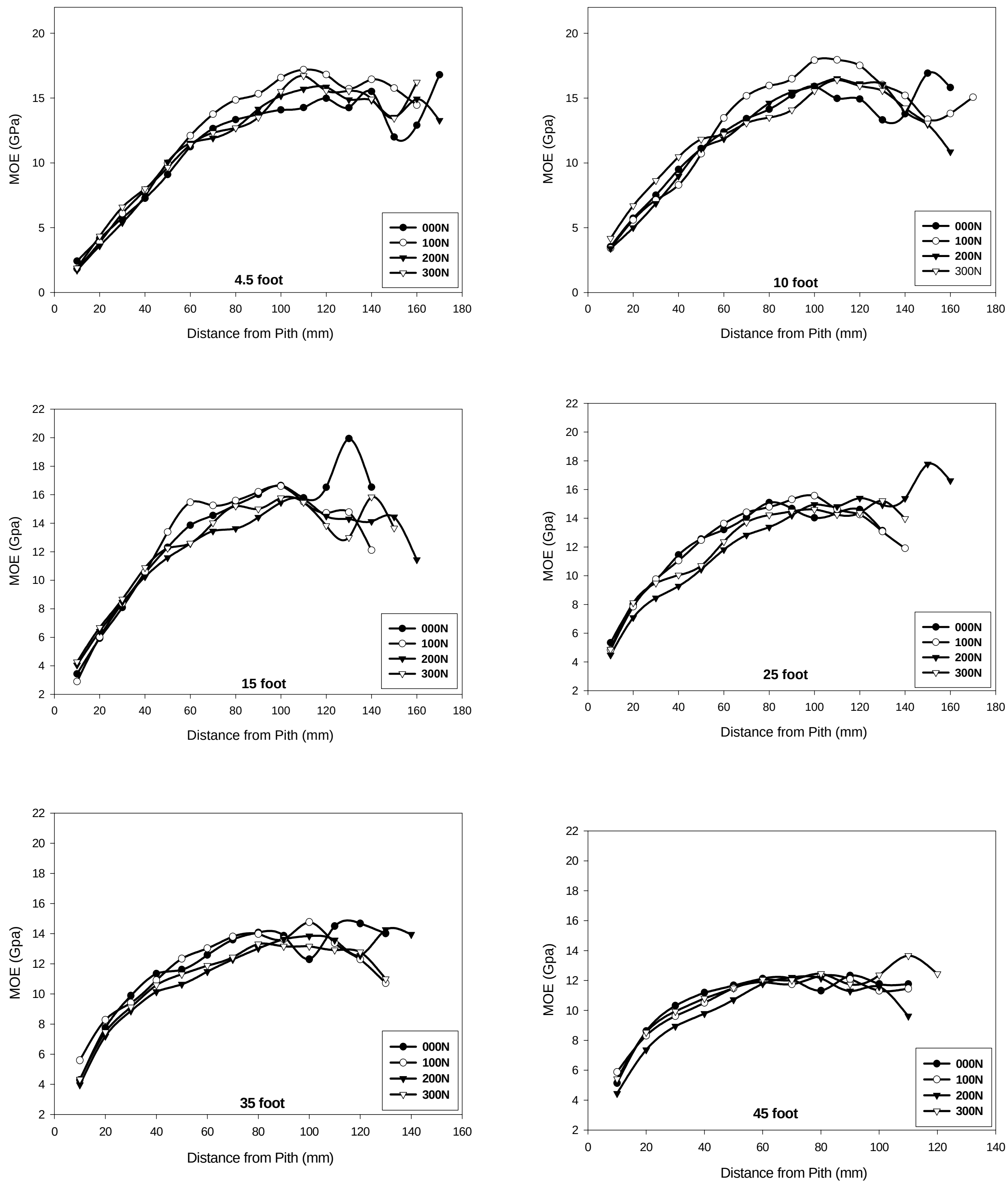

Figure 4.3: Plots of modulus of elasticity (MOE) versus radial distance by treatment at different height levels.

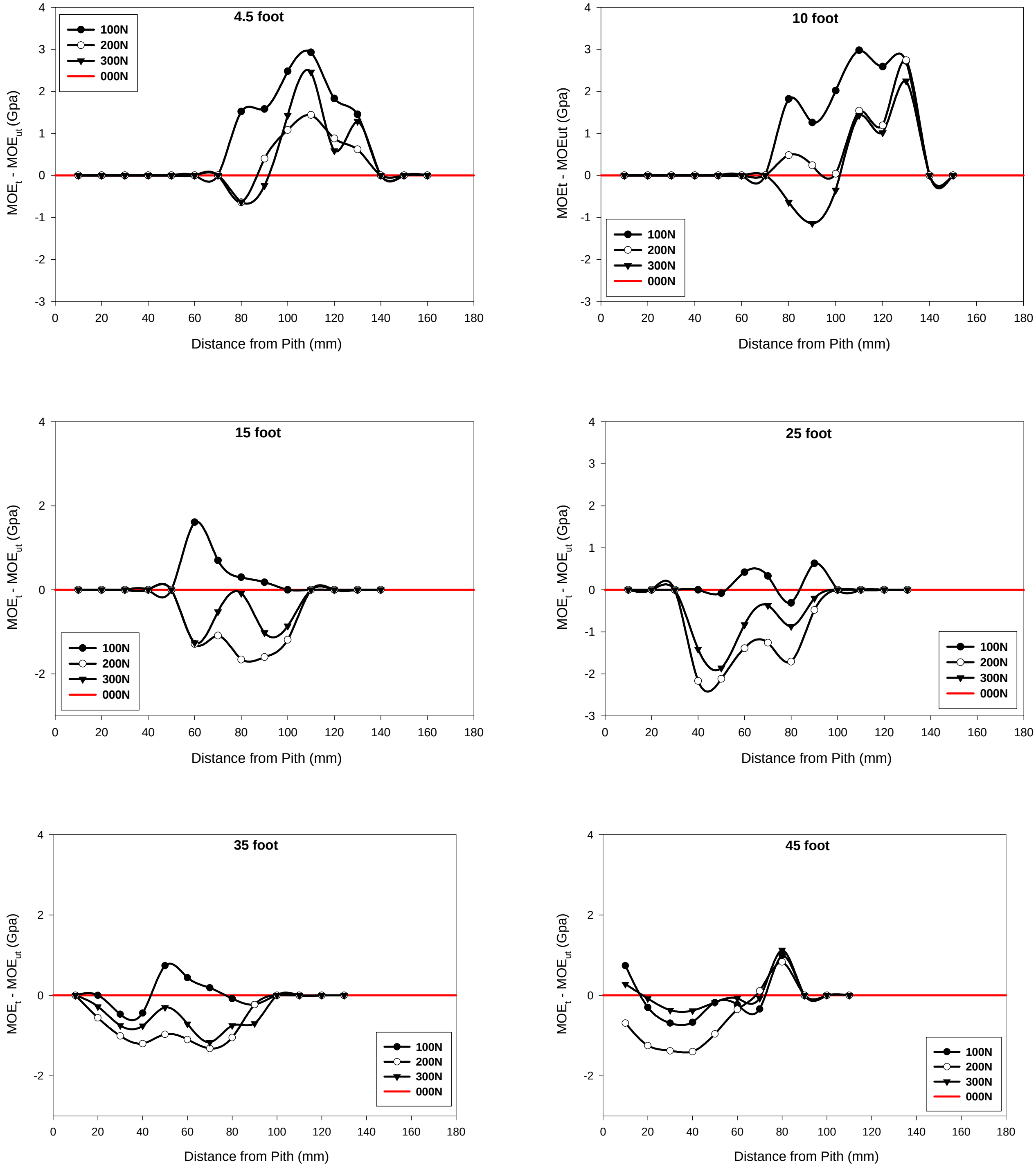

Figure 4.4: Plots of response in modulus of elasticity ($MOE_t - MOE_{ut}$) versus radial distance by treatments at different height levels.

Table 4.1: Parameter estimates and fit statistics for the nonlinear model to predict modulus of elasticity by height and distance from pith.

Parameter	Estimate	Std. Error	t value	p value
$\mathbf{b}_{01}$	16.2065	0.2639	61.42	<.0001
$\mathbf{b}_{21}$	-0.0013	0.000485	-2.59	0.0097
$\mathbf{b}_{02}$	6.9039	0.6864	10.06	<.0001
$\mathbf{b}_{12}$	-0.1107	0.0554	-2	0.0457
$\mathbf{b}_{03}$	-0.0382	0.00306	-12.48	<.0001
$\mathbf{b}_{13}$	-0.0018	0.000367	-4.94	<.0001
$\mathbf{b}_{23}$	0.00003	8.86E-06	3.1	0.002

Fit index: 0.7293
Residual standard error: 2.1589

Residuals:

Min	Med	Max
-8.4021847	0.0770927	8.3742750

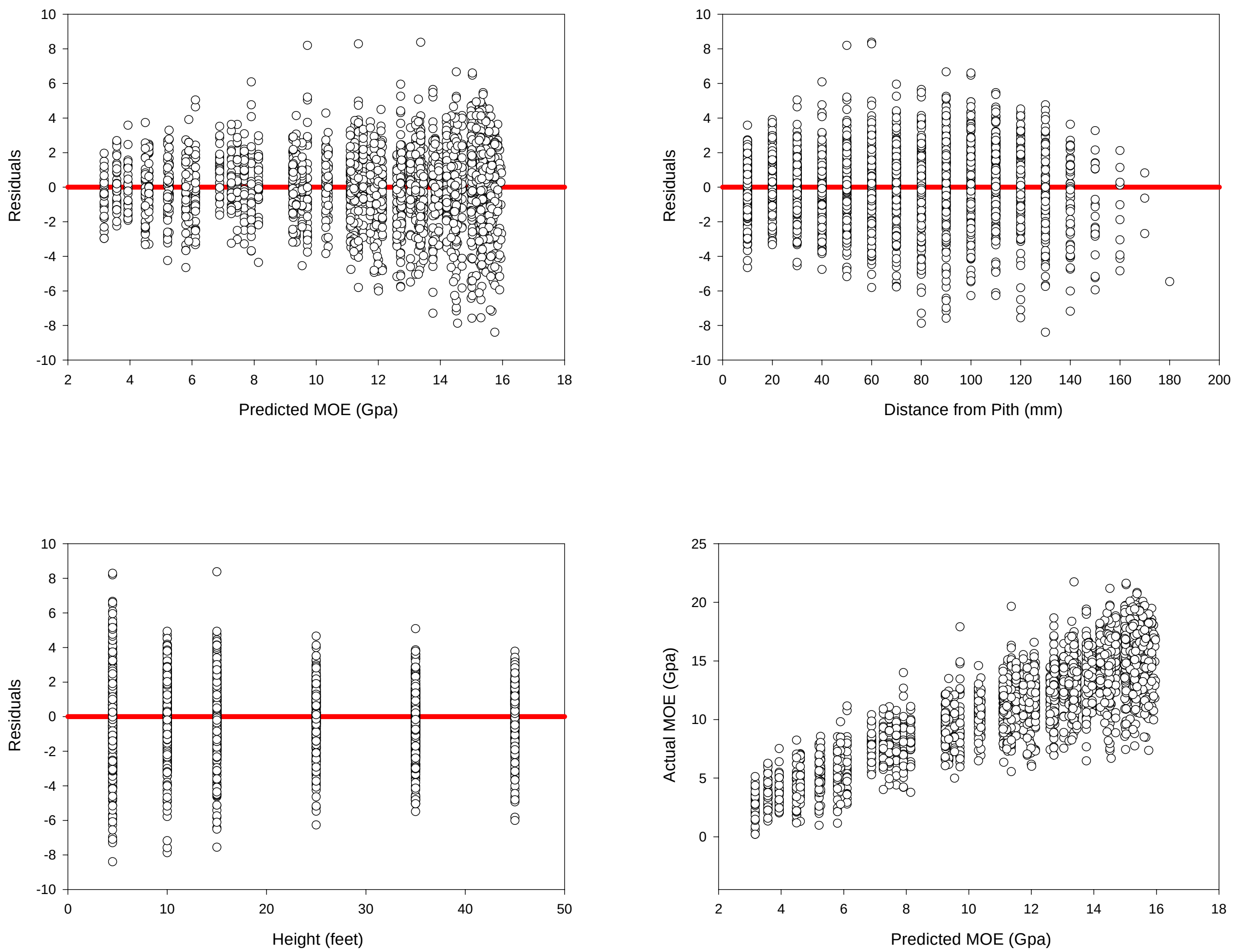

Figure 4.5: Residual plots versus independent variables and actual modulus of elasticity (MOE) values versus predicted values for nonlinear MOE model.

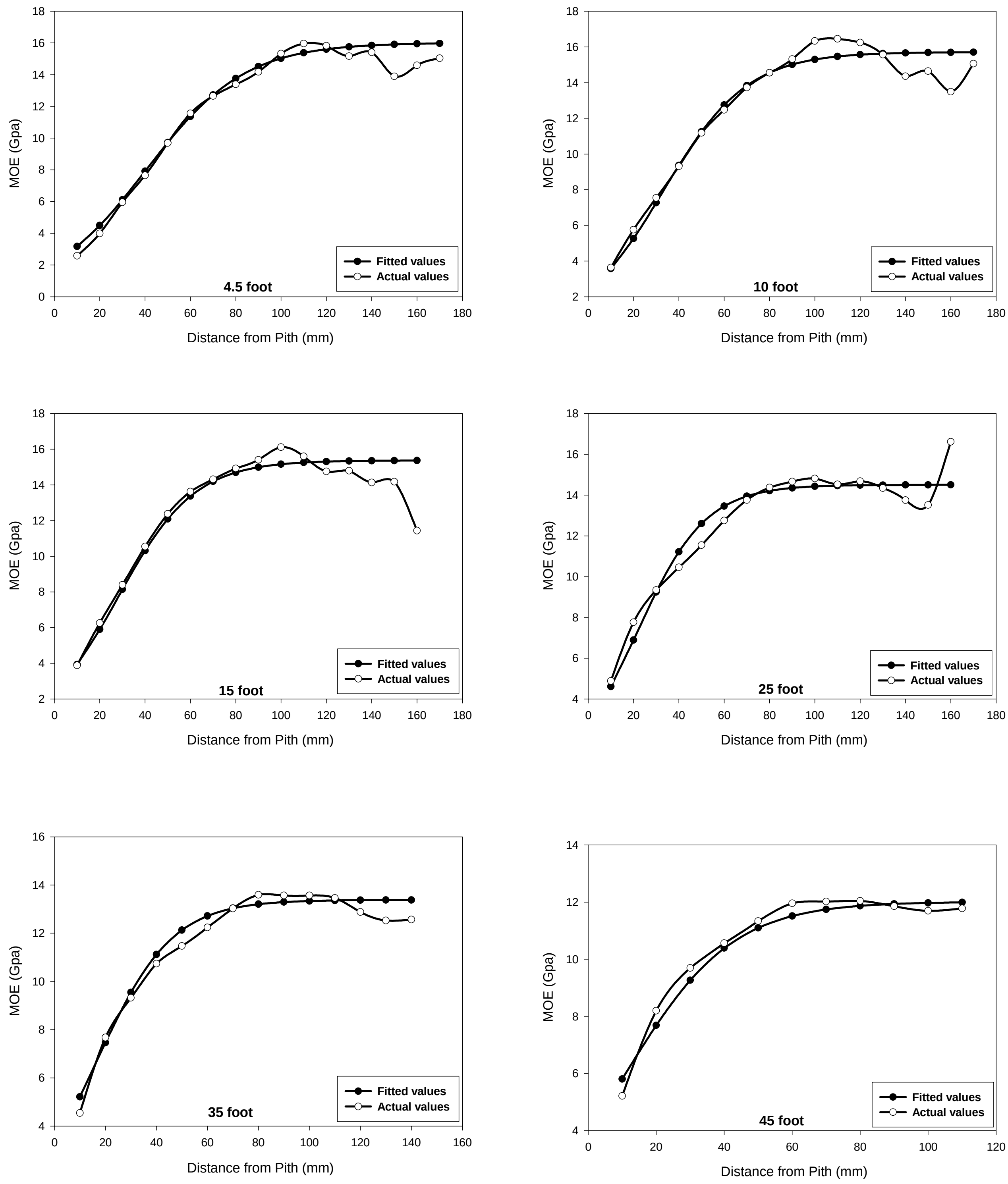

Figure 4.6: Plots of mean actual values versus mean fitted values for the nonlinear modulus of elasticity (MOE) model by height levels.

CHAPTER 5

CONCLUSIONS

Mid-rotation fertilizer application is a widely accepted practice in loblolly pine (*Pinus taeda* L.) plantation management regimes. This is attributed to the significant influence of fertilization in increasing the growth rate of a tree in both biologically and financially attractive ways. However, forest managers and manufactures are concerned about the quality of wood produced from a fertilized loblolly pine plantation. Thirty two trees were collected from a thinned, fertilized mid-rotation loblolly pine plantation located at New Bern, in the lower Coastal Plain of North Carolina. Modulus of elasticity, ring specific gravity and fiber anatomical properties such as microfibril angle, wall thickness, radial and tangential diameter, perimeter, coarseness and specific surface of wood were measured from the radial face of strips made from cores collected at six height levels of these trees. The study was a randomized complete block design receiving four levels of nitrogen fertilizer (Control- no fertilizer, 100lb/acre, 200lb/acre and 300lb/acre along with 25lb/acre of phosphorous with each treatment), each replicated in four blocks. Analysis of variance was conducted on ring basal area weighted whole core average of ring specific gravity, latewood specific gravity, percent latewood and earlywood specific gravity averaged across annual rings from pith to bark. Analysis of variance was conducted on three-year basal area weighted modulus of elasticity, ring specific gravity and fiber anatomical properties such as microfibril angle, wall thickness, radial and tangential diameter, perimeter, coarseness and specific surface. A repeated measure analysis was conducted to examine the variation in treatment effects five years following fertilization and from stump to tip of the tree.

Significant differences were absent among treatments for basal area weighted ring specific gravity, latewood specific gravity, percent latewood and earlywood specific gravity averaged across annual rings from pith to bark. A significant response was observed for a three-year weighted post fertilization average of MOE, ring specific gravity, latewood specific gravity, percent latewood, radial diameter, and perimeter for treatment 300lb/acre. Compared to control, lower values of MOE (1.13GPa), ring specific gravity (0.03), latewood specific gravity (0.03), percent latewood (5%), wall thickness (0.16μm) and higher values of MFA (2.07^{o}), radial diameter (1.53μm), and perimeter (4.39μm) were observed for trees that received 300lb/acre of nitrogen. Little change was observed in wood properties for trees that received lower levels of nitrogen fertilizer (100lb/acre and 200lb/acre). Properties such as earlywood specific gravity, tangential diameter, coarseness and specific surface remained the same following fertilizer application irrespective of the rate of fertilizer applied. A height related trend in wood property changes owing to nitrogen application was absent. A time and height dependent change following treatment in ring specific gravity, latewood specific gravity, percent latewood and earlywood specific gravity was evident from the repeated measure analysis for five-year ring values taken following treatment, but none of the treatments showed a significant difference following fertilization. To conclude, significant changes were absent following mid-rotation fertilization in wood properties of whole cores taken at six height levels; however depending upon the rate of fertilizer applied, a decline in wood quality was observed in growth rings produced immediately after fertilization irrespective of height.

Modulus of elasticity / stiffness of wood is an important wood property explains the quality of wood in terms of its ability to with stand structural deformations. A nonlinear logistic model was fitted to explain the variation in stiffness in a three dimensional way, from stump to tip and pith to bark for trees that did not receive any mid-rotation fertilizer application. The basic model was found to explain the variation in MOE at any specific point within a tree reasonably well. Attempts were made to explain the change in stiffness of wood formed following fertilizer application. However, the lack of consistent response in stiffness from stump to tip and pith to bark owing to fertilization made the explanation of stiffness response in a functional form difficult.

APPENDICES

APPENDIX A

MODEL SELECTION FOR WHOLE-CORE WEIGHTED AVERAGES

Property	***Random effects***	***Correlation structure for height***	***AIC***	***BIC***
Ring Specific gravity	$(\alpha\beta)_{ij,}\ T_{ijk}$	-	-769.3	-767.0
Latewood Specific gravity	$(\beta\gamma)_{jl,}\ T_{ijk}$	-	-750.7	-747.2
Latewood Percent	$(\alpha\beta)_{ij,}\ T_{ijk}$	-	929.1	931.4
Earlywood Specific gravity	$(\alpha\beta)_{ij,} (\beta\gamma)_{jl,}\ T_{ijk}$	-	-877.9	-874.8

APPENDIX B

MODEL SELECTION FOR THREE-YEAR WEIGHTED AVERAGES

Property	***Random effects***	***Correlation structure for height***	***AIC***	***BIC***
Modulus of Elasticity (GPa)	T_{ijk}	-	715.3	718.2
Ring Specific gravity	$\beta_{j,}$ $(\alpha\beta)_{ij}$	SP(LINL)	-629.2	-631.7
Latewood Specific gravity	$(\beta\gamma)_{jl,}$ T_{ijk}	-	-577.2	-573.7
Latewood Percent	$\beta_{j,}$ $(\beta\gamma)_{jl,}$ $(\alpha\beta)_{ij,}$ T_{ijk}	-	1103.2	1100.1
Earlywood Specific gravity	$(\beta\gamma)_{jl}$ $(\alpha\beta)_{ij}$	SP(EXP)	-742.5	-736.6
Microfibril Angle (in degrees)	$(\alpha\beta)_{ij}$	SP(POW)	891.2	893.6
Wall Thickness (*µm*)	$(\alpha\beta)_{ij,}$ T_{ijk}	-	62.6	64.9
Radial Diameter (*µm*)	$(\alpha\beta)_{ij}$	SP(EXP)	716.5	718.8
Tangential Diameter (*µm*)	$(\alpha\beta)_{ij}$	SP(LINL)	533.9	536.2
Coarseness (*µg*/m)	T_{ijk}	-	1815.5	1818.4
Perimeter (*µm*)	$(\alpha\beta)_{ij}$	SP(EXP)	1076.4	1078.7
Specific Surface (m^2/kg)	$(\alpha\beta)_{ij}$	SP(LINL)	1449.9	1452.2